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DEPARTMENT OF INTERNAL AFFAIRS

RECENT GEOLOGICAL HISTORY OF THE DELAWARE VALLEY

below the Water Gap

by

Freeman Ward

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PENNSYLVANIA
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DELAWARE VALLEY
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RECENT GEOLOGICAL HISTORY OF THE DELAWARE VALLEY BELOW THE WATER GAP

By FREEMAN WARD

INTRODUCTION

PURPOSE OF INVESTIGATION

The general geologic facts about this region have been known for many years. Parts of the region have already been examined in some detail, including both bedrock and glacial features. Only one publication describes the glacial geology of the Delaware Valley and that is the excellent work of R. D. Salisbury,[1]—Glacial Geology of New Jersey. This presents a large amount of data but is confined, naturally, almost wholly to the New Jersey side of the valley.

With these known studies as a background it was hoped that intensive detailed work coupled with the newer developments in physiography and glacial geology of the last twenty years might bring to light much new evidence and some newer interpretations of the facts already known.

The work has been confined to that part of the valley from the Delaware Water Gap south to about eight miles below Easton.

Especial attention has been given to glacial phenomena, keeping in mind the following items,—(a) Effects of erosion and deposition, (b) Possible new interpretations of processes, (c) Relationship of the older (Kansan or Illinoian) and newer (Wisconsin) phases, (d) Revision of glacial extension to the south, (e) Bearing on economic geology and archeology.

An attempt has been made to evaluate the preglacial and postglacial erosion to determine in how far the present conditions are the result of preglacial, glacial and postglacial action respectively.

FIELD WORK

The area covered includes the Delaware River proper from the Water Gap to some eight miles below Easton; also the territory on both sides for a distance of one to six miles from the river (See Fig. 1).

For the purposes of comparison, and also to follow up certain clues brought to light by work in the main area, short trips were made up

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[1] Salisbury, R. D., The glacial geology of New Jersey: Geol. Survey of New Jersey, vol. V, 800 pp. and maps, 1902.

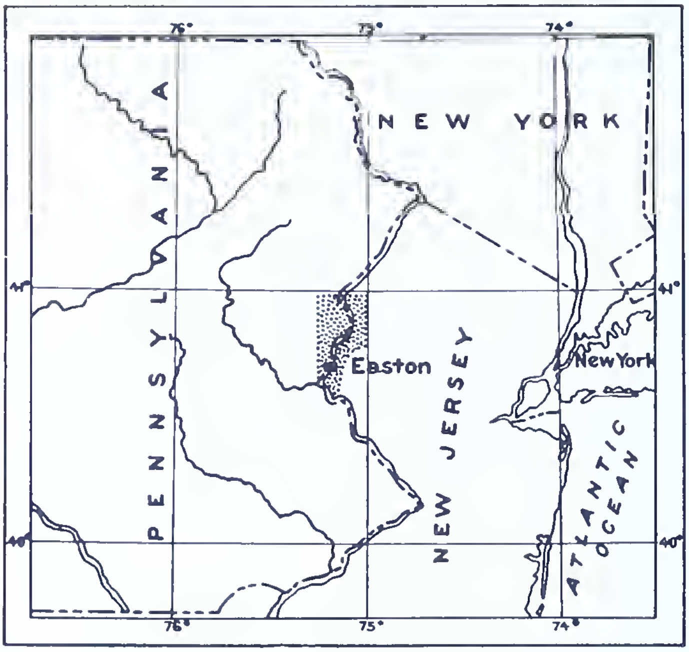

Figure 1. Index map showing location of area.

the Lehigh Valley, along Kittatinny Mountain some miles east of the Water Gap, and north of the mountain.

The field work occupied parts of the summers of 1930 and 1931. The first season's work was done on foot as the best way of securing intimate details. In the second season a car was used, with Joseph Kuebler acting as assistant, in order to cover a larger area, review doubtful localities and bring in specimens.

The Delaware Water Gap and Easton topographic maps were used as base, elevations of terraces, etc. being supplemented by barometric readings.

LIMITATIONS OF FIELD WORK

This region is one of few exposures of bedrock or glacial drift (See pl. 1, A and B). Slopes are moderate to fairly steep with broad flowing, rather than sharp outlines. The area is one of gentle undulating topography (See pls. 1, C and 2, A). Cliffs are rare, that on the southeastern side of Kittatinny Mountain at the famous Delaware Water Gap being the most conspicuous one (See pl. 2, B). There are small local cliffs along the Delaware and along the smaller streams and ravines. Such slopes and climate inevitably resulted in a heavy cover of timber, large tracts of which still remain.

However, crops, pasture, or grass-covered orchards bordered with trees and shrubs, and brush-covered fallow land conceal the rock or glacial material below 99.44 percent of the surface. Plowed fields expose the soil, and road and railroad cuts, if fresh, may expose from one to ten feet of the subsurface rock, rarely 15 to 40 feet. Quarries, sand and gravel pits and cellar holes, if recently dug, afford restricted spots for observation. To the very limited evidence thus obtained, the geologist adds his interpretation of the surface forms which are characteristic of certain geologic phenomena and serve to tie together the available subsurface information.

For instance, the hard Silurian sandstones and quartzites of Kittatinny Mountain, under weathering and erosion, tend to develop a prominent cliff, while underlying Ordovician softer slate and shale form gentle slopes. In fifteen miles of mountain on the Delaware Water Gap map probably the contact of the Silurian and Ordovician can be seen at only one place, and yet this contact can, by inference, be drawn along the whole fifteen miles with remarkable accuracy. Away from the mountain the contrasts of form are not so sharp, but are dependable in lesser degree.

Glacial processes, by erosion and deposition, develop characteristic forms of smaller dimensions—roche moutonnée, moraines, kames, terraces, etc. But, as stated, because of timber in which one often can not see over fifty feet, the tree- and shrub-lined fences, to trace the geologic features requires covering all of the land on foot, especially to observe the finer details sought in this study. Naturally such work is slow.

BEDROCK GEOLOGY

The problem does not call for a close study of the bedrock geology. Hence it is not necessary to present details of petrology, structure, paleontology or historical geology. But certainly the essential qualities of the earth block in which Nature has carved out the landscape, should be known.

The names of the formations, their geologic ages, and general characteristics are given in tabular form in the accompanying columnar section. The surface distribution shown on the areal geologic map[1] (Fig. 2) follows the general northeast and southwest plan which is so characteristic of the Appalachian regions. Brief descriptions, beginning with the oldest member follow.

Columnar section of rocks exposed in the area.

ERAS	PERIODS	FORMATIONS	ROCK TYPES
MESOZOIC	Triassic	Newark	Sandstone, shale, conglomerate. Diabase intrusions.
PALEOZOIC	Devonian	Hamilton Marcellus Onondaga Esopus	Shale and limestone.
		Oriskany	Sandstone and conglomerate.
		Helderberg	Limestone.
	Silurian	Cayuga	Limestone, sandstone, shale.
		High Falls	Sandstone, shale.
		Shawangunk	Quartzite, conglomerate.
	Ordovician	Martinsburg	Slate and shale.
		Jacksonburg	Limestone ("cement rock").
	Cambrian	Kittatinny	Limestone.
		Hardyston	Quartzite.
PRE-CAMBRIAN			Gneiss, schist, granite.

PRE-CAMBRIAN

The greatest variety of rock type is found in the pre-Cambrian group. There are several varieties of gneiss and schist, the latter including schistose talc, serpentine and marble, just north of Easton. Into these rocks granite (largely pegmatitic) has been intruded.

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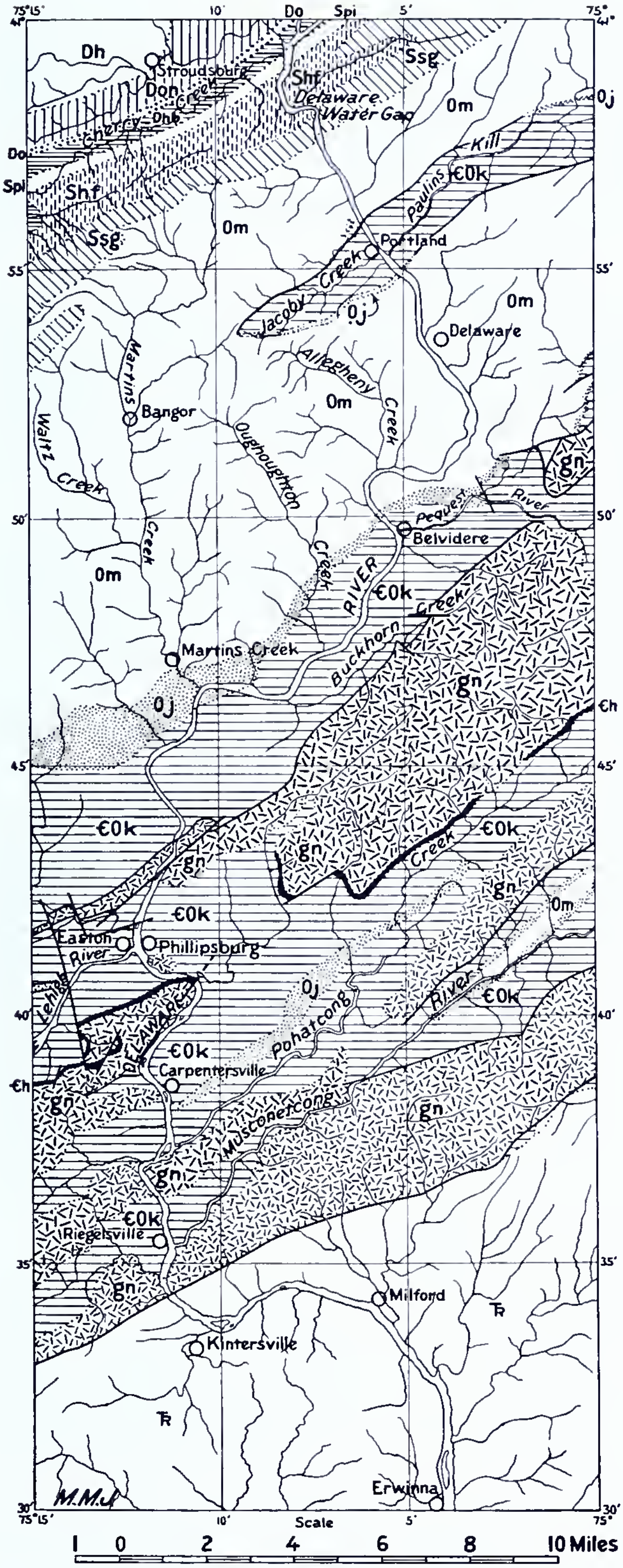
[1] Compiled from XVI International Geological Congress, Guidebook 7, p. 28, 1933; Pennsylvania Topog. & Geol. Survey Geological Map of Pennsylvania, 1931; R. L. Miller, Bull. Geol. Soc. Amer., vol. 48, pp. 1694, 1700, 1937; J. M. Hills, Ph.D. thesis, Lafayette College (unpublished).



TR—Triassic

Dh—Hamilton and Marcellus.

Don—Onondaga.

Do—Oriskany.

Dhb—Helderberg (including Bossardsville).

Spi—Poxono Island.

Shf—High Falls.

Ssg—Shawangunk.

Om—Martinsburg.

Oj—Jacksonburg.

Ok—Kittatinny.

Ch—Hardyston

gn—Gneiss, granite and schist.

Figure 2. Geologic map of Delaware Valley below the Water Gap.

Most of these members are too small in area and too intimately intermingled to be mapped separately. An exception is a narrow band of talc-serpentine rock which has more continuity. Probably the gneiss-schist members are Archeozoic in age, whereas the granite belongs to the Proterozoic era. The series as a whole is resistant to weathering and makes hills. It is found only in the southern third of the area.

CAMBRIAN

Hardyston.—Fine to coarse sandstone, some of it arkosic and conglomeratic, constitutes the Hardyston. Most of it has been metamorphosed into quartzitic types. This is a thin, lens-like member. It borders the pre-Cambrian but is very limited in its occurrence.

ORDOVICIAN

Kittatinny.—The main limestone of the area, which includes dolomitic limestone, is known locally as the Kittatinny. It ranges from light to dark gray, is fine-textured, much of it thin-bedded, and very generally non-fossiliferous. It occurs in the southeastern part of the broad valley south of Kittatinny Mountain and also in coves and intermontane valleys south of Easton. A prominent outlier along the Jacoby Creek-Paulins Kill valleys is completely surrounded by the Martinsburg. The Kittatinny is dominantly a valley maker.

Jacksonburg.—A younger limestone is the Jacksonburg, most of which is quite impure, dark and shaly. This is the "cement rock" used extensively for making portland cement. Some lower beds are nearly pure limestone. This formation is thin and borders the Kittatinny limestone on the northwest. A narrow strip extends from the Delaware River near Carpentersville northeast for about nine miles.

Martinsburg.—Normally the Martinsburg is dominantly shale, but in this area most of it has been metamorphosed into slate, although locally it has some harder and sandier beds. On the whole it is a very uniform dark gray. It occupies a wide and continuous belt in the broad valley south of Kittatinny Mountain.

SILURIAN

Shawangunk.—The most striking topographic feature of the area, Kittatinny Mountain, is composed of the Shawangunk formation, which consists of sandstone and conglomerate that have been metamorphosed into tough, resistant quartzite. An occasional thin, black, slaty parting may be found.

High Falls.—A formation locally called High Falls (synonymous with Bloomsburg red beds), is rather shaly but contains much sandstone. The prevailing color is red, though there are dull greenish beds. It occurs in a rather wide band on the northern and lower slopes of Kittatinny Mountain.

Cayuga.—The Cayuga group consists of limestone, sandstone and shale. Because it is a valley-maker it seldom shows good outcrops. It occurs along Cherry Creek near Stroudsburg.

DEVONIAN

Helderberg.—The basal Devonian formation is the thin-bedded, gray, Helderberg limestone, with inter-bedded chert and conglomerate. It has a secondary, thin parting which gives it a decidedly shaly appearance in many localities. Invertebrate fossils, especially brachiopods, are quite common.

Oriskany.—The Oriskany formation, less than fifty feet thick, consists of chert, sandstone and conglomerate beds. The conglomerate is mostly clean, well-worn quartz pebbles less than half an inch in diameter. The Oriskany and Helderberg occur in Godfrey Ridge.

Onondaga and Esopus.—Dark gray, chertly limestone overlies gray, gritty shale. The shale (Esopus) largely supports Godfrey Ridge. The limestone is exposed north thereof.

Hamilton, etc.—The lower undulating topography in the extreme northwest corner of the area north of Godfrey Ridge is underlain mostly by shale and some sandstone. The shale is rather weak, black or dark gray, with a splintery cross fracture, and is commonly fossiliferous.

TRIASSIC

Newark.—Triassic sandstone, shale and conglomerate, of a prevailing red color, and intrusive diabase occur in the southern end of the area around Kintnersville. The Newark is the only formation in the area which shows practically no effects of glaciation.

STRUCTURE

The structure is typically Appalachian, with many folds, high dips, some faults. The strikes of the sedimentary rocks and the trends of the pre-Cambrian complexes are prevailing northeast. An exception to these generalizations is the Newark formation which has gentle dips, and broad warps.

Those who want more detailed information are referred to the following:

F. B. Peck, Preliminary Report on the Talc and Serpentine of Lehigh County, and the Portland Cement of the Lehigh District: Topog. and Geol. Surv. Comm. of Penn., Rpt. No. 5, 1911.

B. L. Miller, Allentown Quadrangle: Pennsylvania Topog. and Geol. Surv., Atlas No. 206, 1925.

C. H. Behre, Slate in Northampton County, Penn.: Pennsylvania Topog. and Geol. Surv., Bull M 9, 1927.

C. H. Behre, Slate in Pennsylvania: Pennsylvania Topog. and Geol. Surv., Bull M 16, 1932.

TOPOGRAPHY

In this area there are three prominent physiographic zones—I. Appalachian. II. Highland. III. Triassic Lowlands. The first of these has several subdivisions as follows: (a) Ridges. (b) Kittatinny Mountain. (c) Great Valley. (d) Valley Fingers. These are shown in Figure 3.

APPALACHIAN ZONE

(a) *Ridges.*—Figure 3 shows that the ridges are in the extreme northwestern part of the area. There are two types of ridges. Two narrow ridges (Godfrey Ridge is one) have a definite northeast-southwest trend, separated by the narrow valley of Cherry Creek. These ridges are 800 to a little over 1,000 feet high. They have developed on the steeply dipping series of Oriskany and adjacent rocks. North of them, because of a lower dip and lack of prominent resistant members, the ridges have no definite trend and are lower. The district has the appearance of a dissected low plateau. The prominent flats about Stroudsburg, and some of the smaller land forms are depositional in origin.

(b) *Kittatinny Mountain.*—The most striking topographic feature of the area is Kittatinny Mountain which trends northeast and southwest. It continues for many miles each way outside of the area in New Jersey and Pennsylvania. From a distance of five or ten miles to the southeast one is impressed by a cliff-like front bordered below by heavy talus, and an even crest rising to about 1,500 feet above sea level. Actually the crest is not as uniform as it appears at a distance, the elevation ranging from 1,380 feet at Fox and Top Gaps to 1,620 feet on Tammany Mountain, just east of the Water Gap. However, this narrow crest is not at all ragged, for the slopes rise and fall very gradually. Delaware Water Gap is an exception to this. It is a sharp notch bordered by cliffs that drop down to the river just under 300 feet above sea level at this point. The northwest side of the mountain is a rugged slope rather than a cliff.

This mountain owes its prominence and continuity to the fact that it is composed of hard Silurian (Shawangunk) quartzite and sandstone dipping steeply to the northwest.

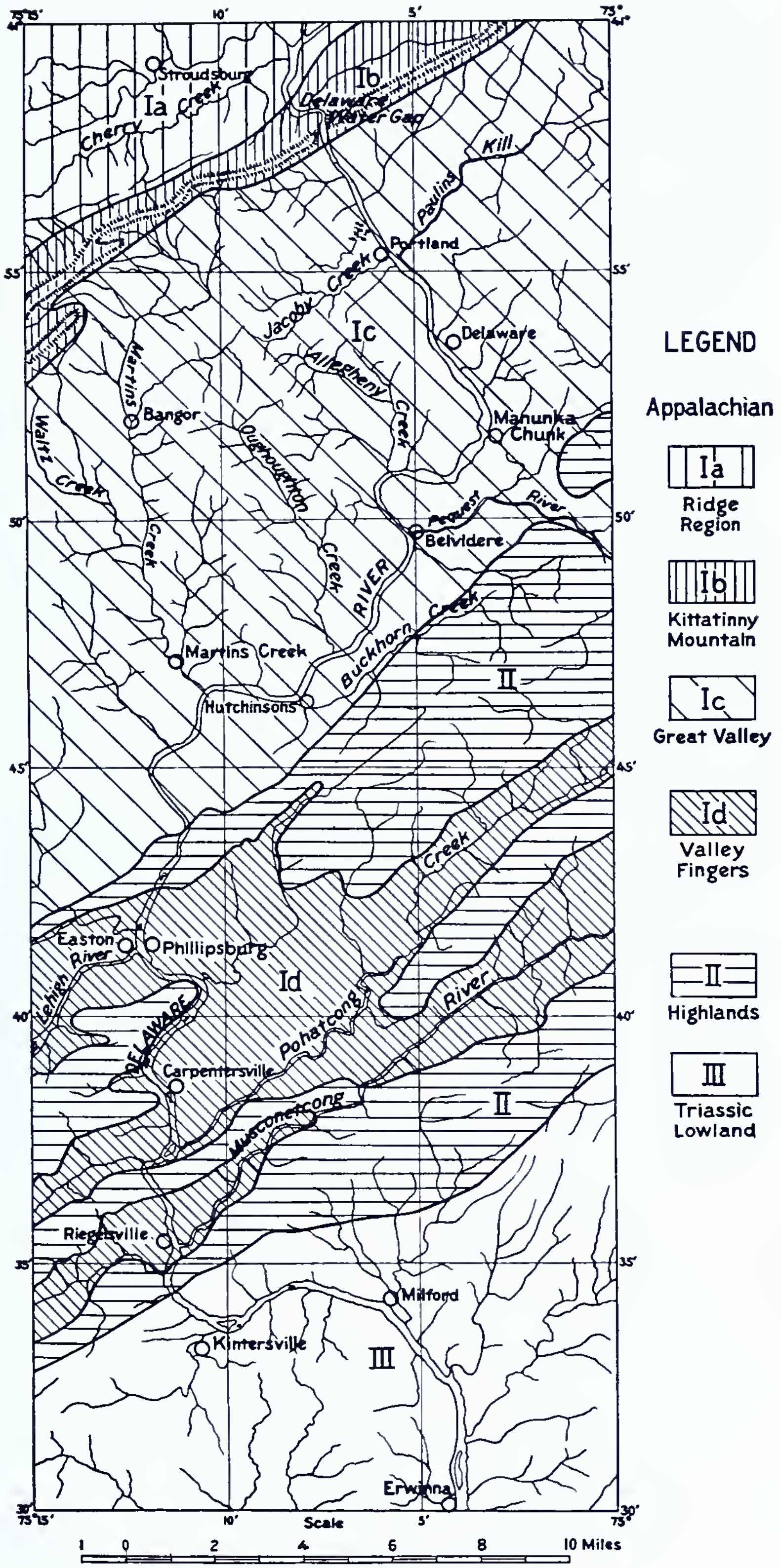


Figure 3. Physiographic zones in the area.

(c) *Great Valley.*—The broad limestone and shale valley is not a single valley but a composite lowland of considerable relief, about ten miles wide, between Kittatinny Mountain on the northwest and the Highland physiographic zone on the southeast. Its trend is parallel to Kittatinny Mountain and both have a common origin as part of the Appalachian system. It is also known as the Kittatinny Valley.

The topography consists of uplands developed on Ordovician slate and shale, and lowlands developed on Cambro-Ordovician limestones. Although both types of rock are well folded, the lack of any resistant member has prevented the development of prominent ridges.

The slate hills are not rugged although a relief of 150-200 feet is common. The rather uniform character of the rock has resulted in smooth flowing slopes with no cliffs, except immediately bordering the river and some of the deeper tributaries. Considerable tracts have a gentle undulating topography. On the other hand there are several prominent more isolated hills. As noted in a later chapter this is a dissected peneplane (Harrisburg), the upper limits of which range from about 800 feet above sea level in the northern part of the area to 600-700 feet in the southern part. Close against Kittatinny Mountain the elevation is approximately 900 feet. Locally more resistant beds make strike ridges of moderate relief.

The distribution of limestone as seen on the map (Figure 2), indicates the position and limits of the lowland. Besides the tract bordering the Delaware from Belvidere southward, the only prominent area of lowland is in the vicinity of Portland, along Jacoby Creek and Paulins Kill valleys that join the Delaware at this point. A smaller area extends up Pequest and Beaver Brook valleys from Belvidere. The topography is not only lower (much of it under 400 feet altitude) but more subdued. The part of the lowland just north of Chestnut Hill is merely an undulating plain. Smaller details of oval hills and knob-like forms are glacial veneer, as is the prominent plain south of Belvidere. This lowland is the one physiographic division where depositional forms occur commonly. As an interesting contrast the two parts of the lowland near Portland may be cited: the small hill irregularity in the Paulins Kill Valley is dominantly erosional, whereas in Jacoby Creek Valley on the Pennsylvania side it is dominantly depositional. Another modification of the lowland from Belvidere southwest is the incision made by the Delaware River and its tributaries; otherwise the relief of the lowland would be slight.

(d) *Valley Fingers.*—What may be called finger-like limestone valleys tributary to the Great Valley occur within the Highland physiographic zone. These enter through the Lehigh Valley at Easton, widen out east of Phillipsburg, and extend as narrow bands along the valleys tributary to the Delaware. With a little imagination one can think of the connecting portion at Easton as the wrist, the wider portion to the east as the palm, and the narrower valleys as fingers. A separate finger follows Durham Creek and the Muscanetcong River. All of these tracts are alike in possessing gentle topography and an altitude comparable to the lowlands of the Great Valley.

HIGHLAND ZONE

The greatest relief and irregularity is found in the Highland zone, 200-400 feet being rather common. Deep valleys and high elevations succeed each other in quick succession. Bordering slopes are all steep though seldom inaccessible. Scotts, Jenny Jump, Pohatcong and Musconetcong mountains are prominent features and there are several less prominent ridges and peaks. The crests of the ridges seldom are sharp and that of Jenny Jump Mountain approaches an undulating flatness. The strike of the steeply dipping gneiss and schist gives a general northeast and southwest trend to many, though not all, of the ridges. The greater resistance to weathering of the pre-Cambrian materials accounts for the greater general altitude of this zone, and the variation in the quality and volume of its several members accounts for the larger relief and continuity of the heights.

As the name implies, this physiographic unit has a greater general altitude than the other zones. As far as actual elevation is concerned, Kittatinny Mountain with its average of 1,500 feet is distinctly higher than the maximum of the Highland zone (Scotts Mountain 1,260 feet). But the former is a narrow ridge whereas the latter is much wider. Furthermore, the abruptness with which the highlands rise above the bordering Great Valley is just as striking along much of its extent as is that of Kittatinny Mountain. In the southern part of this zone there are only a few places where the altitude is greater than 900 feet.

TRIASSIC LOWLAND

The Triassic Lowland zone occupies the district underlain by the Triassic rocks. Its quality as a lowland is less marked here than elsewhere. However, the greater part of the zone is below 600 feet in altitude and the southeastern part is below 500 feet. At a few localities there are short ridges or peaks 800 to 900 feet high. Because of the low dips and small quantity of diabase there are no strong trends to the elevations, and no prominent "trap" ridges that are so common throughout much of the Triassic. Since the lowland is not glaciated, little more will be said about it later.

DELAWARE VALLEY

As has been stated the Delaware Valley courses through all the physiographic divisions of the area. Furthermore is it influenced only moderately by the characteristics of these physiographic units. Reference to the map (Fig. 3) will show that after leaving the Water Gap, the river flows in a nearly straight line south-southeast to Manunka Chunk, then follows a winding course southwestward along the limestone lowland nearly to Easton. Below Easton it winds in a southerly direction to the limits of the Highland zone; across the Triassic lowland its course is more nearly southeast.

The Delaware Valley is narrow, trench-like and seldom more than half a mile wide. Bordering cliffs are common at many places. Besides the Delaware Water Gap there are Weygadt Gap at the northeast end of Chestnut Hill just above Easton, a gap at Bougher Hill about 6 miles (along the river) below Easton, and a lesser one about 2 miles farther down at Rattlesnake Hill. Narrow terraces and flood plains border the valley along most of its course. Bedrock rapids are common below Belvidere, but there are none above, though boulder and cobble rapids occur at intervals.

Other facts about this valley, intimately bound up with the glacial history, will be presented in a later chapter.

SEQUENCE OF EVENTS

As a background for later discussion it is necessary to give a summary of the geologic history of the area as already known and commonly accepted by geologists.

PREGLACIAL EVENTS

Following the formation and deformation of the bedrocks, erosion over a long period resulted in wearing the upper parts of the folds down nearly to a plane (Schooley peneplane). Subsequent uplift has permitted differential lowering of the surface, which however, still reflects the old peneplane surface. The harder rocks, such as those under Kittatinny Mountain and the highland belt, have been worn down slowly and therefore today project as mountains. The limestone and shale areas have worn down most rapidly and today present a low, gently rolling surface at about 400 feet altitude. The slates and some other rocks of intermediate resistance have been lowered to an average altitude of 800 feet for the hilltops.

Until a few years ago it was supposed that these three hilltop surfaces represented remnants of three peneplanes, each resulting from a pause in the uplift of the earth's crust. Recent studies have revealed that this may not be, and point toward all of the surface having been lowered from one peneplane which, if restored, may have been several hundred, possibly a thousand feet above the mountain tops. As formerly understood, the mountain tops are at the former level of the Schooley peneplane, the hilltops at 800 feet at the level of the Harrisburg peneplane and the hilltops in the limestone valley north of Allentown, Bethlehem and Easton, at the level of the Somerville peneplane. Though that idea is not proven, it is still convenient to designate those levels of concordant hilltops as the Schooley, Harrisburg and Somerville "surfaces." The literature on the subject is large. Regardless of the final settlement of these problems, the fact remains that the higher features of the present landscape, and some of the intermediate ones, are the result of long and extensive erosion during preglacial time. The landscape formed in this manner up to the time of the ice invasion is referred to as the preglacial topography.

GLACIAL EVENTS

During the Glacial period the continental ice sheet which covered so much of North America passed over nearly all the area under consideration except the Triassic Lowland.

The Glacial period was not simply a continuous advance of the ice to its maximum extent and then a recession by melting. Rather, it consisted of several stages of advance and retreat with different extreme limits at each stage. In the Central States five glacial and four interglacial stages have been recognized. They are known by the following names, the one at the top of the list being the last or youngest:

Wisconsin—Glacial
  Peorian—Interglacial
Iowan—Glacial
  Sangamon—Interglacial
Illinoian—Glacial
  Yarmouth—Interglacial
Kansan—Glacial
  Aftonian—Interglacial
Nebraskan—Glacial

In eastern Pennsylvania this complete succession has never been proven, but there seems to be no doubt that there were three glacial stages, the Wisconsin, an earlier one—probably Illinoian, and a still older one which is perhaps Kansan.

Type of work.—Whatever the glacier did in the matter of erosion or deposition must have been superimposed upon the already well-defined preglacial topography.

Erosion by the glacier was accomplished in large part by slowly advancing thick ice, armed with rock debris, acting as a rasp; and also in part plucking out looser fragments enclosed by the ice. The glacier was thus able not only to scrape away surface soil and rotten rock beneath it but also to cut into the solid rock below. The result was a smoothing process; rough surfaces were changed to smooth, rounded ones. Hard rock surfaces were marked by parallel scratches and grooves (striæ) made by the rock fragments held in the bottom of the ice. The fragments also were facetted and striated.

Deposition must follow as the ice melted away. All the debris dropped by the glacier is referred to as glacial drift, and much of it was carried many miles before being deposited. There are two kinds of glacial drift: (1) Till, a heterogeneous mixture dropped without sorting as the ice loosened its hold. The forms built this way may occur anywhere the ice reached, are of different shapes and character, and are known by the terms ground moraine (till mantle), terminal moraine, drumlin, etc. (2) Stratified drift, resulting from the action of the melt-water from the wasting glacier working over any drift debris. The material was moved a greater or less distance (often many miles from the edge of the ice) and was sorted into layers or strata by the water during the process. Such drift can occur only where water in large quantity collected and moved, as in the valleys or areas of lower relief. Some of the names applied to the various kinds of stratified drift are—outwash, valley trains, kames, eskers, terraces.

During the absence of the ice other forces were at work. The surface was exposed to the air, so that weathering was active. Rainfall, running water and wind attacked the glacial drift, removed some parts of it and modified all of it. The debris transported a greater or less distance came to rest as stratified deposits.

Relation of earlier and later glacial stages.—A second advance of the ice produced other changes. Naturally, the last glacier on the scene tended to scrape up the drift deposited by any earlier glacier and mix it with any other load it may have secured by cutting farther into the bedrock. However, on the outer margins of the glacier where the ice was thin it might only override and make more compact the earlier drift, especially if the earlier drift was frozen instead of loose. In turn, as the ice melted, its combined load of drift was deposited according to the same laws that governed deposition by the first advance. If the last glacier covered the same territory as the first it might obliterate all traces of the earlier advance, except where subsequent cuts might reveal the younger drift resting on the older. If the last glacier covered less ground than the first, those parts of the earlier drift beyond the reach of the last glacier might still be intact. In this case the two drifts would not be identical in appearance even if each glacier gathered debris from the same bedrock. The older drift, because it had been exposed during the interglacial stage as well as the latest glacial stage, would be more thoroughly weathered. This would show as a darkening of the color, removal of soluble material, developing of rinds, and weakening of all except the most resistant material. The latest drift would have a less weathered, fresher character.

The earlier glaciers extended down the valley as far as Durham, practically to the northern edge of the Triassic Lowland. Remnants of a much weathered drift determine this limit. The Wisconsin glacier stopped just below Belvidere.

The glacial story, especially for the New Jersey side of the valley, is ably presented by the well known physiographer, the late R. D. Salisbury[1].

POSTGLACIAL EVENTS

With the final withdrawal of the glacier the drift of both stages was again exposed to the action of the weather, rain, running water and wind. Where the drift was lacking or became removed, the attack continued on the bedrock. The more the drift was removed or modified the less perfect the record is for interpretation. Postglacial deposits may bury some part of the glacial story book. And over all, in this temperate and humid climate, spreads the blanket of vegetation to mask still further and hide the geological library.

In addition, bodily uplift, tilting, or warping of the land may accelerate or retard the action of running water.

It should be clear that the present condition of the Delaware Valley is not the result of one process or operation. The valley has had a lengthy history and the forces that shaped it during its very long lifetime have left overlapping incomplete records of the whole series of happenings. This interesting complex of preglacial and postglacial events constitutes the problem of this paper.

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[1] Salisbury, R. D., ibid.

GLACIAL GEOLOGY

SUMMARY

The field work has confirmed the more important glacial facts already reported for the area, as follows: (1) The region has been glaciated, as shown by the abundance of erratic and foreign material, by the general smoothing of the hill profiles, and by the presence of striated bedrock. (2) There are at least two kinds of drift, according to age, an older, weathered and a younger, fresher drift. (3) The southern limit of the younger (Wisconsin) ice is approximately as shown on earlier maps. The older ice sheet was more extensive. (4) There is no typical terminal morainal topography in the area except west and northwest of Bangor. (5) There is a prominent kame area in the Jacoby Creek valley. (6) Terraces and outwash occur along the Delaware and some of its tributaries. Many, though not all, of the details associated with the above items and reported by Salisbury and others, the present writer confirms.

Additional facts and modification of current interpretations will be given in the succeeding pages.

WISCONSIN GLACIATION

The usual varieties of glacial drift are present, except drumlins and eskers. The general distribution of the deposits is shown in Figure 4.

The stratified drift is confined almost wholly to the valleys of the Delaware and its main tributaries. No attempt has been made to map the deposits throughout these main tributaries. The deposit along the valley of Paulins Kill is not so continuous as represented in Figure 4. Several small knolls and ridges not covered by stratified drift are too small to show on a map of the scale used. For the same reason the smaller terrace areas within the Jacoby tract are not mapped. One might expect here and there on the uplands some remnants of bedded sands, gravels, or clays marking temporary channelways or pondings, but nothing of the sort has been found. The minor valleys are commonly floored with stratified material, some of which is terraced; but most of this is secondary in origin and so is not represented on the map. One notable exception is the deposit up Slateford Creek. The largest area of outwash is in the Belvidere district. Besides the kame areas shown on the map, there are smaller kames that are not indicated. These are especially common as kame terraces above Delaware. There is more terrace material farther down the Delaware, below Riegelsville, but it has not yet been studied in detail.

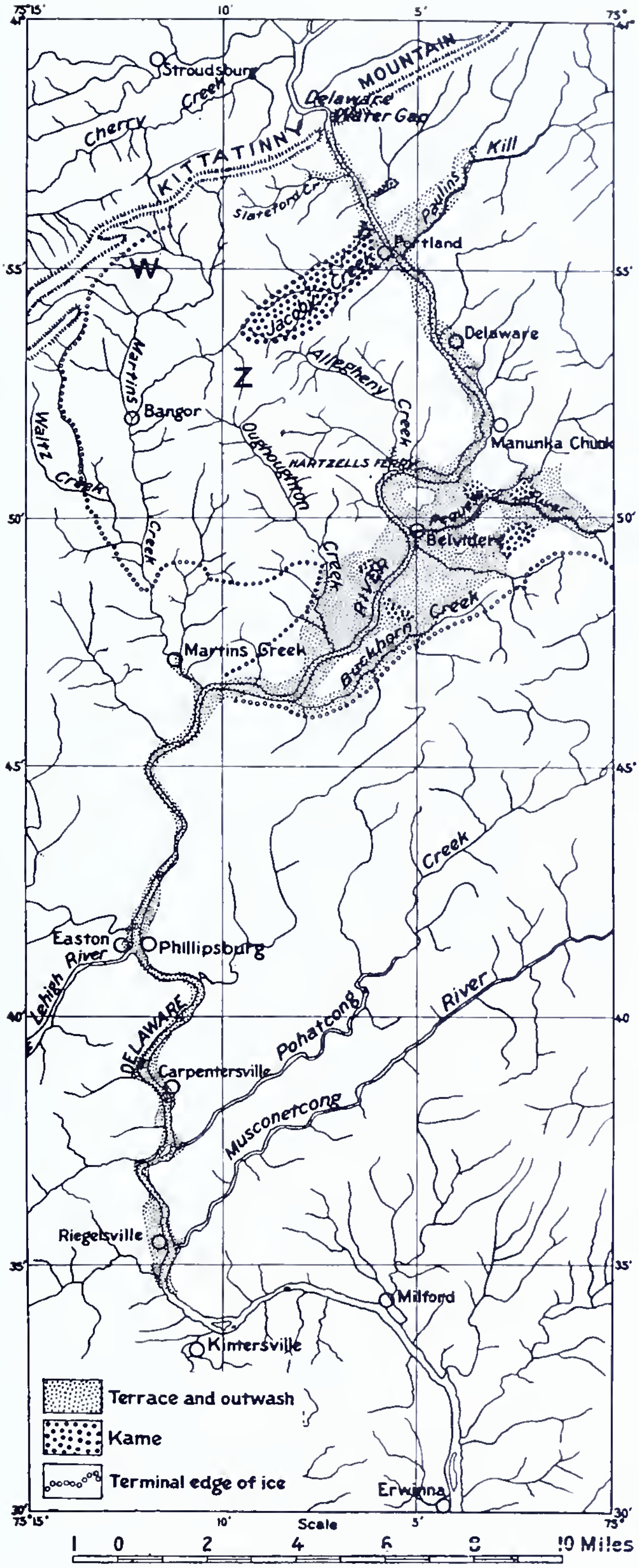

Figure 4. Distribution of stratified drift.

Till occupies most of the territory between Kittatinny Mountain and the terminal edge of the ice that is not overlain by glacial outwash and kame deposits.

There is considerable glacial drift north of Kittatinny Mountain, especially outwash and kames, not mapped because little studied.

Till

The till of this area has most of the characteristics of till everywhere—lack of sorting and stratification, presence of a variety of rocks foreign to the bedrock on which it rests and some of the fragments facetted and striated. A description of two fresh exposures of till follows:

(1) Fresh cut with an 8-foot face which stands up well. No traces of bedding. Abundant angular fragments of slate, all sizes up to a maximum of 3 feet in diameter; these are mostly weak and broken from weathering. Many fragments of quartzite, conglomerite[1] and several varieties of sandstone scattered through the mass; all are clean and fresh and range from very small up to a maximum of one foot in diameter; some are subangular and many are water worn, a few are rounded; no regularity in their distribution. Matrix is a gritty clay, quite compact. Color is a very light yellow-brown or buff similar to faded khaki. Weathering normal. (2) A 10-foot cut, part of which is fresh. Resembles the first except that the quantity of slate is much smaller, some of the other fragments are larger (maximum 2½ feet), and the matrix is more of a sandy loam. Both occur in the slate area.

Some special features of the till need attention:—(1) The till occurs almost wholly as a mantle of ground moraine. There are no drumlins; and there is very limited terminal moraine topography, such as is so well developed in central New Jersey. (2) Very large erratics (15-20 feet in diameter) are lacking. An occasional one is reported by other writers as occuring in the adjoining territory. An eight foot erratic is unusual. (3) The till in six exposures ranges from 1 to 8 feet in thickness. Outcrops of bedrock are common, showing that the present topography is dominated by bedrock rather than by till. In protected hollows till may be 25 or more feet thick, but the average certainly is less than 10 feet. (Salisbury reports a maximum of 135 feet and an average of 8 to 12 feet for New Jersey, not including terminal moraine.) Large swamps are not common. On the ridge that runs from Butzville to Jenny Jump Mountain the till dominates the bed rock topography. Probably it is a thick deposit that blocks the valley and makes Green Pond. This low divide has many small irregularities, with a few kettles scattered here and there. The surface is quite stony with many moderate-sized boulders and a large assortment of smaller fragments. (See Pl. 2, C)

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[1] Bradford Willard: Conglomerite, a new rock term. Sci., n. s., vol. 71 (1930) p. 438.

(4) The till does not rest directly on bedrock; there is (in the half dozen exposures seen) a jumble of slate (shale) fragments between the solid slate and the till. This may be the result of weathering owing to the thinness of the till, but more likely is the result of fraying of the edges of the slate by vibration induced by overriding of the ice. All exposures seen were where the slaty cleavage was at an angle to the surface of abrasion; no exposure was observed where the surface and the slaty cleavage were parallel, though many such combinations must exist. Till was not seen resting on the pre-Cambrian or Silurian; it was seen, poorly exposed, resting on limestone.

(5) Although good exposures of till are rare, glacial cobbles and boulders are abundant in the many stony fields and representative collections are well assembled in the many stone fences. The striking thing about these rocks is lack of local material and the universal presence of foreign quartzite, conglomerite, and various sandstones, practically all from the Shawangunk and High Falls.

(6) One characteristic is not typical of till the world over. This is the uniform presence of waterworm fragments in all till south of the limestone valley (Jacoby-Paulins Kill). Normally some small quantity of stratified material would be entombed in till. An advancing ice sheet is bound to have stratified drift deposited in front of it which may be scraped up and incorporated in the later till. And melt-water from the ice at any stage tends to sort small spots in the till as pockets and lenses of sand or gravel, often with bedding distorted. The case in this district is different. The waterworn fragments are not lenses or pockets in the till but scattered gravel, cobbles, or boulders. (See pl. 3, A) Nor are they simply occasional occurrences; these waterworn fragments occur everywhere in the district. There isn't 25 yards of stone fence anywhere in this district that will not yield a waterworn rock. At wider intervals rounded ones are found. The distinction between waterworn and rounded is illustrated by Plate 3, B and C.

All this suggests that the distribution of stratified drift before the forming of the till must have been wide-spread and uniform. This in turn suggests (but does not prove) that the pre-Wisconsin topography was of moderate relief so that the outwash could be spread rather uniformly, rather than a topography of present day relief which would tend to localize the placement of outwash.

Stratified Drift

Running water, chiefly melt-water from the glacier, carried and deposited the stratified drift. This water found abundant debris brought down and dropped by the ice; hence the streams that formed became loaded and overloaded with rock fragments of all sizes. According to the custom of running water, the fragments became worn by abrasion, were sorted and finally were deposited in beds, maintaining the proper relation between load, size of fragment, and velocity of current (See pls. 4 and 5.)

Since stream action is commonly restricted to natural drainage lines, deposits of stratified drift occur along the valley. Most of these deposits are in the Delaware Valley or its larger tributaries. They occur as terraces, kames, and outwash.

TERRACES

Origin.—Terraces originate generally as follows: (a) For the most part they represent two processes,—first, a filling of the valley to the height now marked by the top of the deposit; this filling usually extends from the edge of the ice down stream for several miles and is known as a valley train; such deposits will be higher near the ice front and will slope down stream to a uniform height (see Salisbury, N. J., vol. V., fig. 38, p. 127); second, removal by erosion of most of this filling, the remnants being the terraces. (b) Another type of origin is less common:—stagnant ice occupies the central portion of the valley; water accumulates along the margins and partly or completely fills the marginal channels. The water may be in such abundance that it covers the ice completely. The water may be quiet enough to be rated as a lake. The debris may be carried by currents along this marginal drainage, or may be dumped in by drainage from

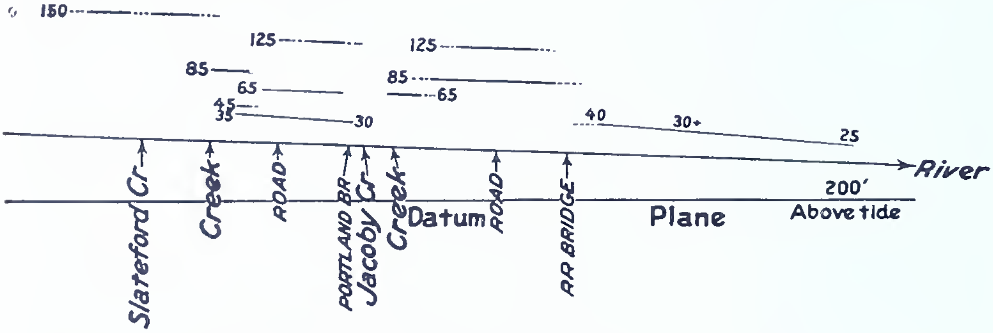

Figure 5. Position and height of terraces.

Heavy lines are terraces in Pennsylvania, light lines, in New Jersey. Figures are height above river.

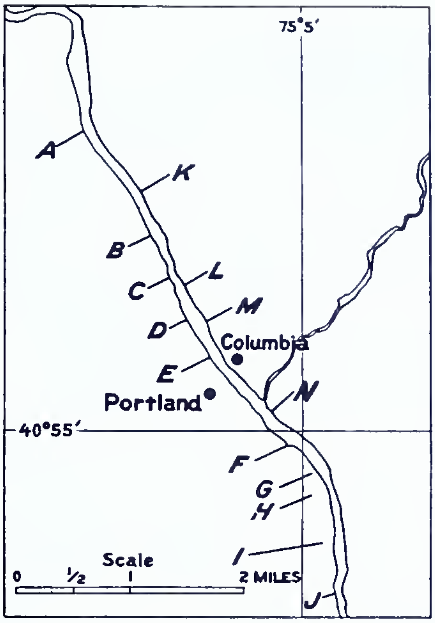

Figure 6. Map showing location of terrace profiles.

the adjoining uplands possibly accumulating with deltaic qualities if the marginal drainage will allow it. In any case the melting of the ice leaves the terrace deposits along the valley sides. These terraces are usually less regular than the more normal type outlined in (a); the irregularity may be a mixture of knolls and flats known as kame terraces.

The terraces of the Delaware Valley are the most extensive and important. They occur at almost any height up to 150 feet above the river. They naturally fall into four divisions as follows, listed in the order of their origin:—

Hutchinsons to Riegelsville.
Belvidere district.
Delaware Bridge to Hartzells Ferry.
Water Gap to Delaware Bridge.

Profiles of many of the terraces are shown in Figs. 7 and 8.

Hutchinsons to Riegelsville.—Terraces start a short distance above Hutchinsons and extend below Riegelsville beyond the limits of the area studied.

In this division there is a main terrace 60-75 feet above the river; and along much of the valley there is one 30-35 feet above the river which, although secondary, is probably also of Wisconsin age. There are also secondary (post-Wisconsin) terraces that are lower.

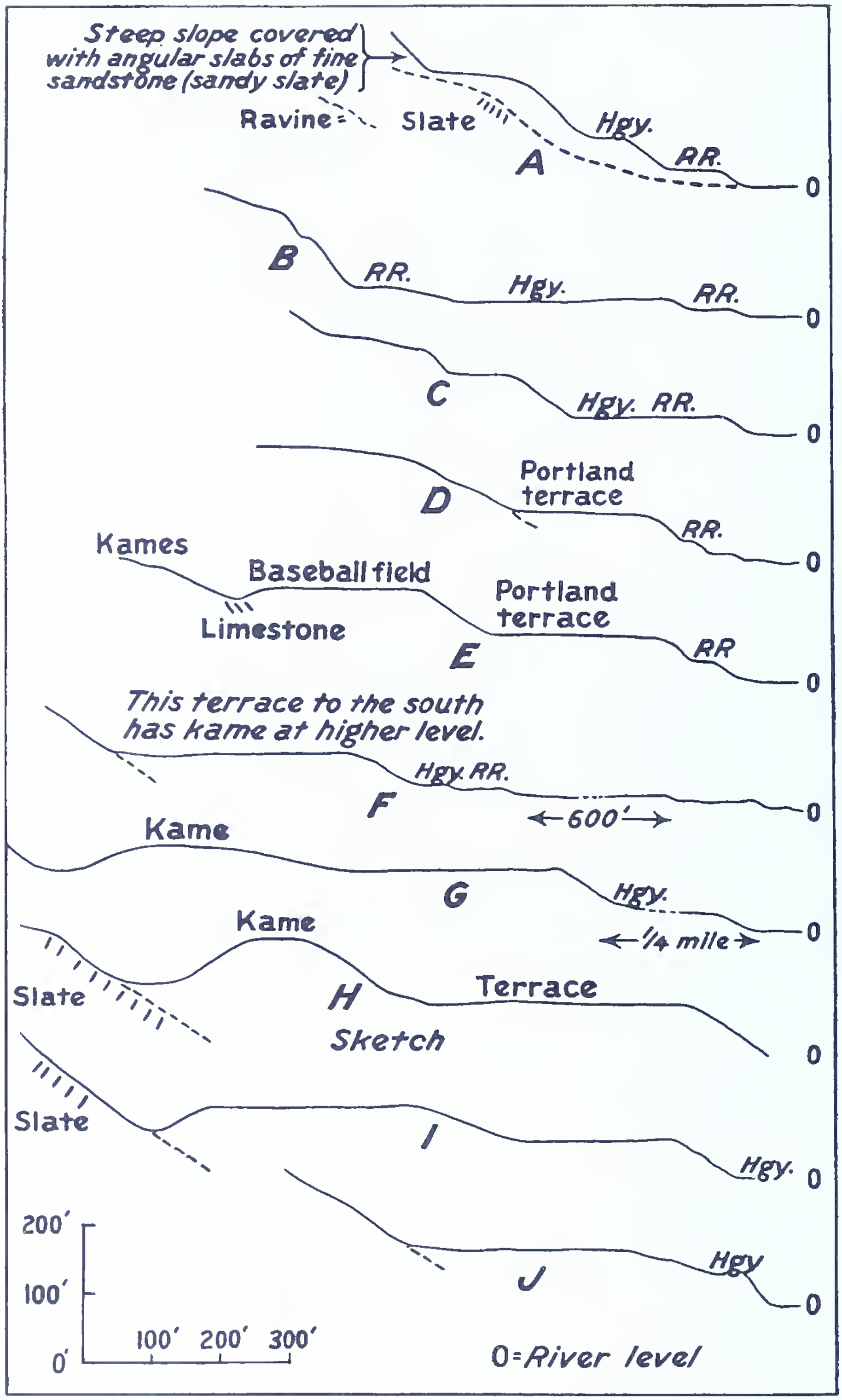

Figure 7. Profiles of terraces in Pennsylvania.

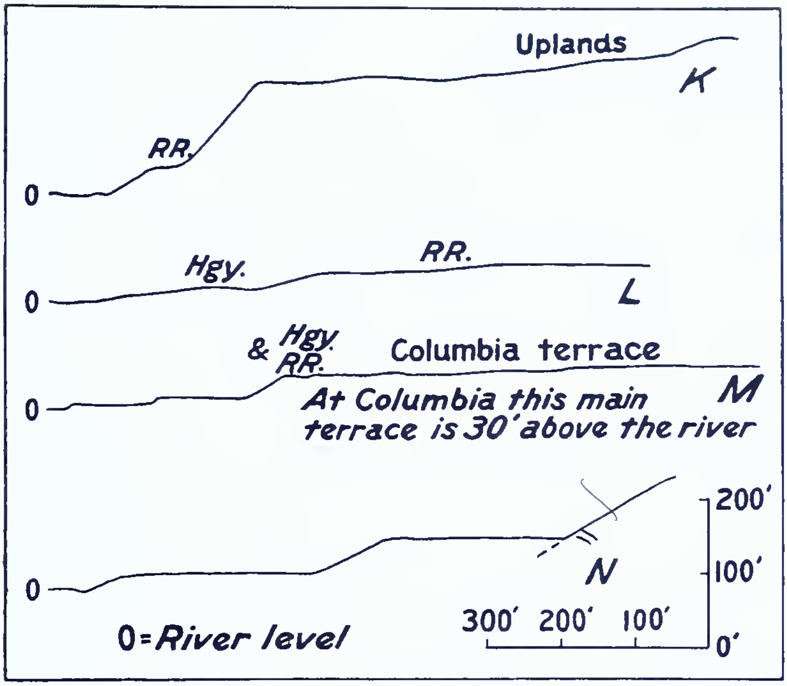

Figure 8. Profiles of terraces in New Jersey.

The main terraces are of the normal type; that is, they are remnants of a former valley train which was built during the recession of the ice tongue (see page 51) from Carpentersville. The recession probably on the whole was rather uniform. No doubt it had its halting points, which would account for some of the slight differences in height and for the gravel bars that occasionally occur in the river. Some of the difference in height is due to the irregularity of the deposition itself, such as the bar just above Carpentersville and another one above Phillipsburg.

As deposition continued upstream, dissection would begin down stream, resulting in a lower terrace developing progressively upstream as the glacier receded.

Belvidere.—The deposits near Belvidere do not all belong strictly to the terrace class. In the borough proper and vicinity, up the river, north along the railroad, and in the adjoining Pequest Valley, the deposits show consistent irregularity as to form and elevation, and kettles are common. All of which indicates, as pointed out by Salisbury[1], that the materials were built around irregular masses of stagnant ice.

"Had the drainage not been influenced, and locally restrained, by ice still lingering in the valley, the gravel deposits would have been built up to approximately the same level at all points on the same parallel. This is not the case either north or south of Belvidere. The gravel reaches very different elevations at different points, and these differences are not the result of subsequent erosion. On one hill it reaches up to 440 feet, on another half a mile distant and a little further up stream it rises to 360 feet only, and on still another in the same latitude it varies from a little above 320 feet to less than 300, and these are the levels of original deposition."

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[1] Salisbury, R. D., The glacial geology of New Jersey: Geol. Survey of New Jersey, V, 1902.

In addition, a wide valley train or small outwash plain extends for about two miles down stream from Belvidere. Some of this is from 120 to 170 feet above the river. Since this is incised by the river, it constitutes a normal terrace.

D.L.&W. bridge to Hartzells Ferry.—One main terrace extends (in fragments) from the D.L.&W. bridge to Hartzells Ferry. At the upper end of the flat at Delaware this terrace is close to 40 feet, at the lower end it is about 30 feet above the river. From this point down stream for the remaining distance the terrace is about 25 feet above the river.

The origin is further discussed in (a) and (b) of the next heading. As there suggested, this is a normal valley train built while the ice front was about at the bridge position and when two of the kame terraces of the next division were forming. Subsequent erosion has of course incised the river channel and removed much of the original fill.

Water Gap to D.L.&W. bridge.—Terraces between Water Gap and the bridge above Delaware may well be rated as abnormal, because of their irregularity and special conditions necessary for their formation. There are five different levels of original (Wisconsin) terraces at 30, 65, 85, 125 and 150 feet above the river. Also there are several secondary terraces at lower levels. Reference to the diagram (Fig. 5) will make clear the following irregularities:

(a) None of the terraces are continuous throughout the whole section, but range from ⅜ to 1½ miles long. (b) The lower ones down stream are not a tapering off of the higher ones up stream. (c) There is usually an abrupt change from one terrace to another along their length and on the same side of the river; for instance, from Portland north the highway runs on a prominent terrace 65 feet above the river, another one parallels it for a shorter distance but 60 feet higher, then both stop to be succeeded within 175 yards by one at 85 feet above the river extending for about 600 yards; this in turn is gone and another at 150 feet above the river continues to near the Water Gap. (d) Except in one place the terraces do not match in height on the two sides of the river; for instance, opposite Portland, from Columbia upstream about a mile the terrace is 30-35 feet above the river, with the 65-foot and 125-foot levels missing. (e) One item not represented on the diagram is of a different sort:—the 125-foot terrace has small knolls rising above it: above Portland these merge into the kame area of Jacoby Valley; below Portland in one or two places a small ravine separates the terrace and valley wall (see profiles, Fig. 7, G and H). Another point to be noted is that none of the four upper terraces is represented in the next division down the valley.

HOW TERRACES WERE MADE

As to the origin of this complex series of terraces:—In point of time, the terrace division farthest down stream was deposited first. Within this division the following seem to be the most probable happenings and sequences:—

(a) The ice had withdrawn until only a tongue ending just above Delaware filled the valley to a depth of 125 feet. It did not fit the valley snugly, for there was considerable space along its margin. This space was filled with debris deposited by melt-water. In addition, on the Pennsylvania side, the drainage from the uplands piled up mounds and knolls on top of the flatter deposits made by the melt-water. On the New Jersey side similar mounds might have been made and removed by subsequent erosion, but this sort of deposition was less likely because the drainage was diverted along the nameless creek just to the east, and the Paulins Kill valley was probably still occupied by stagnant ice. In other words this 125-foot terrace is a kame terrace in large part. During this stationary stand of the ice tongue the melt-water from the front of the glacier was building a valley train which when completed was to be the terrace from Delaware to Hartzells Ferry.

(b) The ice tongue, holding to about the same southern limit as in (a) had, however, wasted on the surface until it was only 85 feet thick. The marginal melt-water now built a deposit as in the first case but at a lesser altitude. The marginal drainage conditions from the uplands on the New Jersey side also must have been as in (a). On the Pennsylvania side the marginal drainage may have been less and it cut the ravine now bordering the higher terrace on the upland side. The porous nature of this terrace resting on the more impervious slate of the valley wall would tend to allow this development. The construction of a valley train in front of the ice would continue.

(c) The ice front recedes about a mile while the thickness is reduced to 65 feet. Building of terrace by marginal deposition as before.

(d) Withdrawal of the ice until its front was north of the Water Gap.

(e) Readvance of the glacier until its terminus was about half a mile below Slateford Creek, the thickness of the ice being 150 feet. The highest terraces of the valley were then deposited as a fill along the margin of the ice. Furthermore, a valley train was built down stream from the ice terminus, remnants of which constitute the 35-30-foot terrace at Columbia and above, which slopes down stream as such a deposit should.

(f) Final withdrawal of the ice as the Glacial period ended.

From the above outline of events one might expect more extensive deposits. But erosion was removing part of the record all the time. As the protective ice withdrew, the marginal fillings must have slumped somewhat, and would be removed where thinnest and more readily attacked by run-off from the uplands. The valley trains tend to be incised as the ice front recedes, and migration of meanders may sweep away large portions of such deposits.

Another condition may have existed during item (e) above. The re-advance of the ice with increased thickness means another climatic swing to severity; one would judge that though of short duration it was intense. Hence we would expect unusually heavy snow banks and glacierets or hanging glaciers along the cliff of Kittatinny Mountain and the high uplands adjoining. Later, as the warmer stage returned and the glacier waned, rapid melting produced a rush of water down these short, steep slopes. This would account for the kames at the mouth of the unnamed creek east of Browning, and the very coarse deposits at high level up Slateford Creek. This flood, as indicated by the thickness and very coarse texture of the deposit, would in part be turned upstream along the margin of the ice tongue. The marginal downstream current would be checked, and result in the deposition of fine material at this one spot. Such a fine-textured deposit occurs near the Water Gap north (upstream) of the present high terrace, though there is no current bedding to prove direction.

Two other hypotheses for the origin of these terraces may be mentioned, though each one encounters more difficulties than the modified kame terrace scheme outlined above:—(1) Successive halts of a generally receding ice sheet; at each halt a valley train built from the ice edge down to the preceding halting place. The upstream portion of one valley train would thus be higher than the downstream portion of the adjoining one. (See Salisbury, fig. 38, p. 127.) But this does not account for the great variation in elevation nor the overlapping. It is hardly possible to think of the 150-foot terrace being laid down originally as a continuous flood plain, filling the valley from wall to wall, and later largely removed. Currents capable of bringing so much fill with such a very coarse texture (many cobbles and small boulders) would not stop so abruptly as the terrace limits show. Furthermore, if the ice sheet extended across the valley and on to the uplands, there should be more evidence of these recessional halts outside of the valley. (2) Some system of morainal and ice dams which would hold the water at a given level and determine the height to which deposition should reach, with subsequent partial removal by erosion. The chief objection to this, and seemingly an unsurmountable one, is the very coarse texture of the material, scarcely possible in ponded water.

Texture and composition.—The materials of the terraces are well exposed in section only at 12 or 15 places: at several other localities the internal qualities of the deposits were poorly exposed. Throughout the valley the deposits are well classed as coarse in texture, varying naturally, from less coarse to very coarse. The coarsest contain an abundance of cobbles and numerous boulders (2 to 8 feet as a maximum). The greater part should be classed as coarse gravel with cobbles. These terms refer to a given deposit as a whole, and do not exclude the presence of some sand and gravel beds or lenses. Locally, as would be expected, the finer sizes are present in greater abundance.

Another generalization is that the upper parts of a given deposit are coarsest. The terraces from Water Gap to Delaware have the coarsest textures. Other divisions lack the progressive change in texture downstream that might be expected. No perceptible diminution in texture occurs between Martins Creek and Carpentersville, a distance, along the river, of eleven miles. But at Riegelsville the texture on the whole is less coarse. South in the vicinity of Trenton sand is dominant, coarse gravel is lacking, and there is only a small quantity of ordinary gravel. The shifting of the glacier front between Water Gap and the bridge above Delaware, the influence of tributary drainage, and the greater opportunity for floating and stagnant ice caused the less systematic variation downstream.

The bedding is distinct in the good exposures. Some localities show rather even bedding, but more show considerable variation both vertically and horizontally within short distances. Single beds of very coarse material, such as coarse gravel with abundant cobbles, may be 8 to 15 feet thick. Hence a shallow cut would not reveal the bedding in such material. Cross-bedding, except in sand lenses, is not strongly marked in each exposure, though locally it is prominent. Plates 4 and 5 show bedding and other characteristics of several of the cuts.

The material shows only a moderate effect of transportation by water. Water worn pieces are naturally in great abundance, but well-rounded ones are not particularly common. Subangular fragments are numerous, and striated ones are occasionally found.

The material is composed mostly of quartzite, conglomerite and various sandstones of Silurian age; limestone, chert, slate and shale are common but variable; adjoining and below the pre-Cambrian tracts, fragments of gneiss and granite are very generally present but never very abundant. These, as will be seen, are the same rocks as occur in the till.

The weathering is not excessive. Whereas there is porous chert, friable slate, and soft impure limestone, there is no unusual development of limonitic stains, no development of weathering rinds; the quartzites and sandstones are tough and fresh.

Thickness.—The thickness of the terrace deposits is not known because well records are lacking and in only one place, up Slateford Creek, does a deep cut show the material resting on bedrock. The deeper cuts range from 20 to 100 feet. One would expect the deposits to be as thick certainly as the faces of the terraces are high, plus probably additional material below river level. This indicates that thicknesses of 100 feet are not rare. Salisbury reports a thickness of 93 feet opposite the village of Delaware. On the other hand, in the outwash areas below Belvidere bedrock is exposed in some of the cuts, which suggests that an irregular surface of limestone is buried to a uniform height by stratified drift at no point especially thick.

Older terraces and rock terraces.—The older (Illinoian) stratified drift makes terraces below Hutchinsons but higher above the river. Description of these terraces will accompany a discussion of the older drift in later pages.

Rock terraces are neither abundant nor prominent, but do occur at high levels along the valley. These too will be discussed later (p. 56).

KAMES

Kames differ from terraces in both form and origin. Instead of the flat top and steep front typical of terraces, kames are small hills or rounded knolls. They occur singly but more commonly in groups, merging irregularly into each other and often having depressions of varying depth between. Their crests may or may not rise to a common level. They are depositional forms, and not the result of unequal erosion of a once continuous deposit. They may be associated with and superimposed on terraces, as west of Portland. They originate where rapid deposition by active currents is localized and where blocks of stagnant ice have been buried (discussed further in a later paragraph).

In this area groups of kames occur in five places—(1) Valley of Jacoby Creek. (2) About 1½ miles north of Columbia where the unnamed creek leaves the uplands and enters the limestone lowland. (3) About 1½ miles northeast of Belvidere, near where Pequest River turns southwest. (4) About two miles due east of Belvidere, between the railroad and the uplands. (5) About two miles south of Belvidere. These locations are shown in Figure 4. Besides these groups, isolated kames occur on some of the terraces between Delaware and the Water Gap.

Jacoby Creek.—The group of kames along the valley of Jacoby Creek is by far the largest and will be described in detail. This valley is occupied by kames from Portland to Johnsonville, an air-line distance of 3½ miles. The group averages three-quarters of a mile in width. It is a striking assemblage of knolls, irregular knobbly ridges and depressions. Individual knolls are 20 to 50 feet high and a total relief of 100 feet may be found in half a mile. This deposit is being worked commercially by the Portland Sand and Gravel Company, hence many good cuts are available for observation and study.

Next to the topography the most striking fact about the deposit is its very coarse texture. Whereas sand and gravel are plentiful, cobbles and boulders in a matrix of coarse gravel are of very common occurrence. There is an abundance of boulders 1½ to four feet in diameter, many 4 to 8 feet, and one boulder 10 by 10 by 12 feet is in place in the midst of less coarse stratified material (See pl. 6). Astonishingly this is the largest boulder seen in the area, being larger than any erratic found in the till. On the whole the western portion of the deposit has fewer large boulders.

The bedding shows rapid changes both vertically and horizontally; fine, coarse and very coarse materials merge quickly into each other and no type of texture is restricted to any particular position or horizon. Cross-bedding is common and usually is nearly parallel to the surface of the knolls, as is to be expected since the form of the knolls and knobby ridges is the result of deposition.

Subangular stones are numerous but most of them are water worn: on the other hand, well rounded ones are not common. Many stones, particularly the larger ones, are striated.

Quartzite, conglomerite, and various types of sandstones, of Silurian age, are the chief rock materials, as in the till and terrace deposits, with the addition of much local limestone. One piece of coarse pegmatitic syenite was found, the only one of this sort seen anywhere in the area.

The thickness of the kame deposit must be considerable. Single cuts have faces of 15 to 45 feet. A suction dredge operated to a depth of 30 feet below the floor of one pit but pumping had to be abandoned because cobbles clogged the pipe. Bedrock was reached in the bottom of one pit, and a well near Johnsonville penetrated 152 feet before striking bedrock. No doubt the limestone floor is very irregular but the kames which rests on it probably are 100 to 150 feet thick at many places. Plate 6 shows the character of this kame deposit at several places.

The origin of this deposit has been suggested above, but the details of the process are not wholly clear. Two difficulties present themselves: One is the very coarse texture;—boulders two to five feet in diameter require flood currents for transportation. Some of the boulders, probably all of the largest, were aided in their movements by ice. But there are plenty of waterworn boulders, up to a maximum of five feet in diameter, showing that they have been rolled along by rushing water. A ten mile an hour current in an open valley is not rare during flood seasons, but special conditions must have existed to provide greater currents in Jacoby Valley at the time of deposition. Because the materials are piled irregularly rather than spread uniformly across the valley we infer that considerable stagnant ice must have been present. The ice may have been a continuous mass, thoroughly cracked and with wide crevasses, or it may have been huge blocks well separated. In either case the ice localized the deposits. The whole mass of ice may have been buried. If the ice were 80 feet thick and covered with 20 feet of mixed gravel, etc., the spaces between the ice would have 100 feet of material. When the ice melted the whole deposit would settle, leaving knolls where the least ice had rested. Variability in the size and thickness of the ice blocks would result in a corresponding variability in the final deposit. But in a valley partly blocked by ice masses high velocities of meltwater currents would be difficult to maintain. The simplest explanation is to assume the valley partly blocked by ice, with strong currents running off from the ice front nearby. Since the coarseness diminishes somewhat towards the western end of the deposit, the currents must have come from the east, which in turn points to an ice front with a general north and south trend. Another point to keep in mind is the prevalence of limestone. Most of this limestone is the Kittatinny rather than that from the Silurian-Devonian north of the mountain.

The most reasonable solution of the problem of kame distribution is suggested in part by the different conditions in the Paulins Kill valley on the New Jersey side. This limestone valley has relatively thin deposits of stratified drift. Kames are lacking, except for the small tract close against the highlands 1½ miles north of Columbia. Bedrock shows abundantly. A very irregular limestone surface is partly buried by valley fill. The glacial movement was southwest, nearly parallel to the limestone valley. The origin of the kames seems then, to be somewhat as follows: the glacier moved down Paulins Kill valley and up Jacoby Creek valley, eroding limestone fragments from the bedrock. Much of this material worked into the ice, a common process in modern glaciers. Withdrawal of the glacier later left ice blocks in Jacoby Creek valley, probably because it was lower. On further more rapid withdrawal voluminous currents from the ice front swept most of the rock debris into the Jacoby Creek valley, again because it was lower, making the kames. This means that the Delaware Valley was not so open as today. Either there was a dam at the mouth of Paulins Kill or, more likely, the trench-like character of the Delaware Valley had not yet developed. Much later the Paulins Kill drainage flowed down the Delaware and during the process removed a good deal of the deposits that may have been formed earlier in the Paulins Kill valley.

The origin of kames described above is associated with another series of events discussed in pages 53-63.

Columbia.—The small tract of kames north of Columbia had a less involved origin. This tract is at the mouth of a large creek that enters the limestone lowland from the uplands at this point. No doubt the abrupt change of gradient caused rapid deposition by a heavily loaded stream. This would tend to produce irregular mounds of coarse stratified drift rather than a more uniform deposit. There may have been some ice blocks here also, though they are not essential in this case. The structure is not exposed.

Belvidere.—In the development of the kames 1½ miles northeast and 2 miles east of Belvidere, stagnant ice masses doubtless played a prominent part, as has been stated for all the deposits of the Pequest Valley. At the latter locality active drainage from the adjoining upland probably was a contributing factor.

The set of kames 2 miles south of Belvidere is considered by earlier writers to be part of the terminal moraine of the Wisconsin glacier. It cannot be the terminal moraine, for Wisconsin till has been found farther down the valley. It may be a recessional moraine. On the basis of the topography—irregular knolls, knobbly ridges interspersed with kettle holes—this may be either a recessional moraine or a group of kames. The internal structure, whether made of till or stratified drift, would decide that point. Unfortunately the writer could find no clean cross-sections. The few road cuts have slumped and washed down so that no structure is visible. Following the criteria laid down in a later paragraph (p. 33) the evidence favors stratified drift as the dominant material because—(a) The rocks in stone fences lack the extremes in size so commonly found in till. (b) There is an abundance of waterworn material. (c) The few cuts seen had a cleaner matrix than till usually possesses.

The receding glacier may have halted here. Bedrock seems to be near enough to the surface to have caught large ice blocks, through and around which the melt-water could have moved. Near the river the bedrock shows an abrupt change from the smoother roche moutonnée surface to one with small, sharp strike ridges having a relief of 5 to 15 feet (see pl. 7, C), similar to those seen at low water in the channel at Foul Rift nearby. Plunging currents coming from the ice front could have differentially eroded the limestone in this manner, while a short recession of the ice would have diverted the melt-water to a new channel. Some ice blocks may have been large enough to produce local bodies of till on melting.

SLATEFORD

The only deposit of stratified drift that has been found above the Delaware Valley and really in the uplands is well up Slateford Creek. The top is crossed by the road on the north side of the creek at an elevation of 620 feet above sea level. The extent is not known, but the deposit does not now reach the old slate quarry on the tributary creek to the south; nor does it seem to extend more than half a mile up Slateford Creek. It probably extends across the flat about a quarter of a mile north of the road, and merges into the high terraces along the Delaware to the east. A 60- to 70-foot face is exposed at the site of the old slate quarry opened in the bed of Slateford Creek. In the west part of the cut 12 feet of obscure material is underlain in succession by 8 feet of boulders, 7 feet of cobbles, and 4 feet of boulders. The basal beds are obscure but rest on slate. Bedding is plain (see pl. 5, C). In the east part of the cut the upper boulder bed thins down to 4 or 5 feet and then dies out. Below it is more coarse gravel and gravel with cobbles. The beds are naturally cemented so that some of them overhang. Probably this deposit was formed during the last advance of the ice.

COMPARISON OF TILL AND STRATIFIED DRIFT

Till is unassorted, lacks bedding except for an occasional small lens or pocket of sand or gravel; the stones are angular or subangular, many of them showing striations; boulders are common; matrix usually clayey. Stratified drift is sorted into beds or strata; stones are waterworn, hence usually lack striæ; matrix commonly sandy; boulders not common.

These standard differences enable one to distinguish the material in good exposures. But in this area exposures are few and poor, and one has to depend largely on shallow cuts or surface conditions alone.

Difficulties in distinguishing till and drift arise because—

1. Both have an abundance of subangular stones.
2. Both may have boulders.
3. Both have waterworn stones.
4. The upper bed of stratified drift may be 6 or 8 feet thick, hence a 2- or 5-foot cut would not show bedding.
5. In deeper cuts, weathering and rain wash may obscure bedding.
6. Some stratified drift is not simply flat-topped valley fill or terrace.
7. Terraces may be rock terraces with a veneer of till.
8. Striated stones are not common, and may be found in both.
9. Thick vegetation may obliterate or obscure all evidence.

Distinctions based on fundamental differences of origin are—

1. While both may have many subangular fragments, the stratified drift has more and the till less of the waterworn stones.
2. A wide range of size in rock fragments in a single exposure suggests till, whereas a limited size range suggests sorting of stratified drift.
3. The knobby kame topography is stratified drift.
4. Rock terraces are of small extent and area; continuous terraces of considerable size usually are stratified drift.
5. A weathered, rain-washed exposure of stratified drift looks cleaner than till, especially after a rain, because its content of clay is less; for the same reason, when dry the material (unless very coarse) tends to slump under the influence of gravity.
6. In deep and reasonably fresh cuts, the standard distinctions hold.

Even with the above distinctions well in mind, experience shows that one may still be undecided about many cases.

STRIAE

Striated bedrock surfaces are not at all common. From Kittatinny Mountain southward only at seven places were striæ seen. Other investigators report six more occurrences in this area. All are shown in Figure 10. North of the mountain striæ are more common but since that area is not included in this report, only a few are plotted on the map.

Comparison of Figure 10 with the areal geology map (Fig. 2) will show that three of the sets of striæ are on quartzite (Shawangunk), seven on slate, two on limestone and one on pre-Cambrian rock. As mentioned before, slate preserves striæ only when its cleavage planes coincide with the surface of the bedrock. Otherwise, the slate is vibrated into a loose, frayed condition by the passage of the ice. At one of the limestone localities there are three sets of striæ (S.40W., S.55W., S.75W.). Of these the S.55W. direction is the most common and probably, though not positively, the S.75W. is the latest.

It is believed that some of these striæ were made during the Illinoian and some during the Wisconsin stage of glaciation. The evidence in support of this will be better appreciated after the characteristics of the Illinoian drift are presented, so the complete discussion is reserved for pages 54, 55, 64.

WISCONSIN ICE FRONT

Original study and mapping of the maximum extent position of the Wisconsin glacier have been accomplished by Lewis, Salisbury, and Behre.[1]

In general the boundary has an east and west trend and is considered to cross the Delaware just below Belvidere. After crossing Martins Creek the boundary trends northwest to north as it approaches Kittatinny Mountain. The writer agrees with the general position as outlined but disagrees in the details.

One would expect a definite terminal moraine to mark the position of the ice terminus. The writer has seen most of the terminal position of the glacier from Townsbury, New Jersey to Kittatinny Mountain north of Bangor, Pennsylvania. From just north of Ackermanville, Pennsylvania up to the base of the mountain there is a good terminal moraine. It is topographically well marked, with a typical knob and kettle expression and a surface well sprinkled with erratics, none of which are large. (See pl. 7, A and B.) The width varies from half a mile to a mile. There are some breaks but on the whole this moraine is traceable about six miles. It is best developed west and northwest of Bangor.

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[1] H. C. Lewis, Terminal moraine in Pennsylvania and western New York: Pennsylvania Second Geol. Surv. Report Z, 1884. R. D. Salisbury, The glacial geology of New Jersey: New Jersey Geol. Surv. vol. V, 1902. C. H. Behre, Slate in Northampton Co., Pa.: Pennsylvania Geol. Surv. Bull. M 9, 1927.

But nowhere between Townsbury, New Jersey and Ackermanville, Pennsylvania, a distance of about 18 miles, is there an undoubted terminal moraine topography, except the small remnant blocking the preglacial valley north of Butzville. The farthest reach of the huge glacial chisel is not indicated by a distinct change in topographical expression in the bedrock, for ridge profiles show a continuous, uniform outline in passing from non-glaciated to glaciated territory. The bedrock almost entirely controls the present topography.

Criteria.—Since these are the facts, other and less striking phenomena must be used in following the ice margin. The following criteria were used:—

1. The most obvious determinant is the presence or absence of foreign material, i.e. drift. But it is seldom accurate to place the boundary as far as any stray fragment may be found. All drift would not stop abruptly at the ice front. There must usually be some spreading of fragments in front of the ice, either as local outwash or by gravity and rain wash subsequent to the withdrawal of the ice. It is logical to consider the ice edge to have been at the point where abundant drift fragments occur and where a scattering distribution begins, though one should not expect the boundary to be sharp and absolute. The topography fronting the ice modified this. Where the topography is flat or slopes away from the ice, scattering fragments may be expected all the way from 50 yards to more than a quarter of a mile beyond the ice edge. Where the topography rises steeply in front of the glacier, scattering fragments may be accepted as marking the ice margin. There remains the personal equation in the matter of the term "abundant." The writer has considered this to mean that fragments are found in the fields without hunting and usually in such quantity that stone fences have been built of them. A modifying factor is the vegetation: where the cover of grass, crop or forest is thick, borderline determinations are obscure.

2. The tracing of fragments should be considered conclusive only on the crests of spurs, ridges or wider uplands. Down well-marked slopes and in valleys, running water and creep will remove the fragments well beyond the ice boundary and often in quantity.

3. In certain localities the character of the bedrock brings in other criteria. This applies almost wholly to the pre-Cambrian areas. (a)

In non-glaciated areas of pre-Cambrian rocks weathering has developed soil of a deep tan (in places rather reddish) color and in the till-covered tracts, soil of a light buff color. Salisbury remarks that in plowed fields this color difference may even be rather sharp and striking. The writer did not have an opportunity to see such fields but found that the color criterion holds well. (b) The soil is rather deep in the nonglaciated areas and is plainly residual, showing the dominance of local rock. Partly weathered feldspars are common in such soils and over the granitic bedrock, quartz gives the soil a gritty character. These qualities are largely lost in the till mixture. (c) Outcrops in the nonglaciated areas are quite characteristic. One seldom finds prominent, cohesive outcrops except on very steep slopes or bordering active streams where erosion has a chance to remove the weathered material. Usually the outcrops are groups of large angular, easily broken blocks fallen apart and subdued by weathering. There are no roche moutonnée effects. By contrast the glaciated outcrops, although few show striations, are trimmed off, have roche moutonnée effects, and are tougher under the hammer.

The limestone of the lowland, where the boundary should cross, is so thoroughly covered with terrace deposits and outwash that no chance is offered to test any of these criteria. The only one that would be expected to apply would be the character of the outcrops.

In the slate belt these criteria could hardly be applied at all, except that in the nonglaciated areas shale chips are very abundant in the soil.

4. Between boundary locations identified on crests, the ice front should be drawn as a lobe down the intervening valley.

Modifications of established boundaries.—The positions of the ice front as determined by Lewis and Behre respectively are marked on the map (Fig. 9). The writer finds that the general trend of the ice front was similar to that determined by them but he does not agree in detail, as the map shows. The locations were made in accordance with the criteria presented above.

On the New Jersey side, the writer made only slight changes from Salisbury's line from Oxford Church northeast, and settled upon a definite line from that point west and southwest to the limestone valley, a district where Salisbury had not mapped the boundary with any definiteness. In one locality, the high part of Jenny Jump Mountain, the writer made a radical departure from the New Jersey report. He believes that the top of the mountain was not overridden by the Wisconsin glacier. The decision is based chiefly on the character of the outcrops, as explained under criteria 3c above. Drift fragments are present but they possess the well weathered characteristics of the Illinoian drift. The Wisconsin ice must have reached nearly to the top of the mountain, as shown by the boundary line marked on the map (Fig. 9).

In one important respect the writer differs widely from any of the previous investigators. This is in the interpretation of the boundary in the limestone valley. Behre, since his investigation was concerned primarily with the slate, did not carry his terminal boundary across the limestone. Lewis (p. 55 of Rept. Z) states that a "—range of drift hills crossing the Delaware one mile south of Belvidere represents the southern limit of the great continental glacier and its true Terminal Moraine—." His map (Plate 8, p. 532) shows this same position. Salisbury says (p. 259): "The small isolated moraine area two miles south of Belvidere, rising above the general level of the valley train, is the only example of true moraine material in the Delaware Valley south of Belvidere." This is also marked on his map, Plate XXVIII.

If the terminal moraine crosses anywhere near Belvidere it certainly must be along the line of irregular hills about two miles south of the town and to which Salisbury refers. These hills make a zone approximately half a mile wide trending about northwest on the New Jersey side and about due north on the Pennsylvania side of the river, thus extending nearly the whole width of the limestone valley. The topography rising 20 to 60 feet above the outwash is irregular, with many knolls and short knobby ridges together with a number of kettles. It has the "knob and kettle" forms so common in terminal moraines. The few road cuts are so poor that the internal structure can not be determined exactly. The rocks are dominantly the quartzite, conglomerite, and various sandstones seen everywhere in the area. Limestone occurs moderately, but pre-Cambrian rocks are very scarce. The external evidence indicates a group of kames with smaller portions of till, rather than a typical morainal till accumulation with occasional spots of stratified drift. The presence of scattering striated stones is not at all decisive, for they occur both in till and stratified drift. There is an abundance of coarse gravel and cobbles and relatively few boulders. The surface is not bouldery. The stone fences are big. In them the coarse gravel and ordinary-sized cobbles predominate; large cobbles and small boulders are not abundant, though present. From a distance the stone fence looks like a pile of ordinary gravel, i.e., the range of size is limited and thus the collection would ordinarily not come from till. There are more rounded stones than striated ones, and still more waterworn ones. The surface of the limestone bedrock here is very irregular and noticeably higher than the adjoining parts of the lowland. The combined data suggest very strongly that across the lowland at this location the limestone was enough higher to cause ice blocks to run aground. Stratified drift was spread around these ice blocks when the ice front was just to the north on its recession. The blocks may have been large enough to produce local deposits of till as they melted. The scarcity of pre-Cambrian rocks indicates that there was no general ice supply coming off of the uplands to the northeast. This means that this is a group of kames (see page 31) built during the later waning stage of glaciation.

The origin above outlined does not exclude a minor halting of the ice at this point, which would accentuate the irregularity and height of the limestone floor. An independent evidence of minor halting is of a different sort. On the Pennsylvania side of the Delaware the limestone outcrops freely in the channel (Foul Rift) and on the adjoining bank up to 60 to 80 feet above the river and from 100 to 250 yards back from it. About 1½ miles above the mouth of Oughoughton Creek the character of the outcrops changes sharply. On the north the outcrops are smoothed off even with the general sod level. On the south small, jagged serrated ledges, striking N.45E. project three to six feet above the surface and less commonly 8 to 15 feet (pl. 7, C). Apparently the ice held at this line long enough for the outrushing waters to erode the limestone differentially, as is being done today in the jagged outcrops of Foul Rift. On further withdrawal of the ice a short distance the water found outlet along a different and lower passage.

Down the limestone lowland from this group of kames below Belvidere most of the hills that rise above the 300-foot level are covered with till. The other workers in this area (except Lewis, who apparently didn't note it at all) believed this till to be of Illinoian (or Kansan) rather than Wisconsin age, so naturally left it out of the picture. This is not wholly the case however. The distinctions between Illinoian and Wisconsin drift are discussed more fully in the following pages. The chief difference is the degree of weathering, the older Illinoian being more deeply weathered to a deep tan, while the Wisconsin till (already described) is a light buff. The larger quartzite fragments of the Illinoian may even have a rich bronze or russet tone. The till for two miles downstream has an intermediate color: as a whole its tone is not so light as the typical Wisconsin, nor so dark as the typical Illinoian till, while the fragments are in part various russet shades and in part normal colored and fresh. All of this suggests that the two types of till are mixed. The mixture could have been made by the Wisconsin glacier bringing fresh material and incorporating it with older, more weathered Illinoian debris. In other words, the Wisconsin glacier occupied the limestone lowland for several miles below the kame area. I believe it covered the lowland on the New Jersey side down to the mouth of Buckhorn Creek, and on the Pennsylvania side to a point about half a mile above Martins Creek. From these points the ice persisted as a narrow tongue confined to the Delaware trench down certainly as far as Carpentersville, N. J., several miles below Easton. The reasons for this latter belief depend in part on a comparison of the Wisconsin and Illinoian drift. So, presentation of evidence supporting the ice tongue theory is given later (p. 51) after the Illinoian glaciation is discussed.

ILLINOIAN GLACIATION

The description of glacial deposits and phenomena, which has so far made up the bulk of this paper, has had to do with the latest or Wisconsin phase of the Glacial period. There was an earlier phase (probably of Illinoian age) of glacial activity in the region. The glacier came from the north and affected the same general territory as the Wisconsin phase. However, the earlier glacier was larger and so travelled farther. They both must have overridden essentially the same rock terrain and so would have gathered and distributed similar glacial drift. And yet the two drifts today are not identical. The qualities wherein the Illinoian drift differs from the Wisconsin drift furnish the material for the following discussion.

Weathering

The fundamental cause of this lack of identity is weathering. The Illinoian drift, though derived from the same bedrocks, is older and so has had more time to be modified by this universal process.

Weathering is in part a mechanical process, termed disintegration, and in part a chemical process, called decomposition. The visible effects of weathering are (1) color changes, such as the yellow-browns of hydrated iron oxides, and whitening developed when feldspar decays; (2) weakening and softening of the original substance; (3) removal of soluble materials. If only portions are soluble, the material may become porous or cavernous.

Naturally, the processes start on the exposed portions first and make their way into the material. Hence the surfaces of rocks show more effect than the parts within. Narrow zones of alteration or rinds are developed on the solid rock and much wider zones of a similar sort within the more open deposits of drift. Rock fragments in a loose-textured deposit or on the surface may develop rinds of a different sort in response to alternate wetting and drying, for capillarity will transfer material from the inner to the outer part of the fragment.

Drift deposits, because of their unconsolidated character and fine-textured matrix, have an enormously greater surface open to attack than solid bedrock. On account of these physical differences the drift may weather (chiefly by decomposition) extensively while the bedrock (or large fragment in the drift) will change only moderately in the same length of time.

Time

Quite naturally the rate of weathering is slow from the human standpoint, although the processes are active enough to call for careful selection of building stone. Experience shows also that even where good material has been used, replacement of masonry is often necessary after an exposure to the weather for a century. Thus the matter of time is an important part of this problem. Was there time enough between the Illinoian and Wisconsin stages for weathering to advance to any great depth?

Where the drift of one stage can be seen resting on that of an older stage, there is opportunity to estimate the time. The upper part of the older drift may be much weathered, with a good soil, with some interglacial vegetation upon it. It may be cut by erosion, or it may have an interglacial deposit of peat, loess or other material containing warmer-weather, interglacial fauna. Thus the time elements are (1) rate and distance of withdrawal of ice, (2) development of soil, (3) migration of flora and fauna into area, (4) forming of deposits, (5) rate of readvance of ice. In addition we have post-Wisconsin time measured by varves and by the time necessary to erode the 7-mile Niagara gorge.

Through a study of such phenomena an estimate has been made of the length of time since the Illinoian glaciation. The figure is 150,000 to 250,000 years. Hence there is plenty of time for a great deal of weathering. The question of time in relation to glacial stages and the preservation of striæ is discussed on page 64.

Results

The Illinoian drift consists of typical deposits of both till and stratified drift. By typical is meant that the till is an unsorted mixture of fine-textured matrix containing larger fragments which have a wide range in size; while the stratified drift shows an orderly arrangement into beds, a more open texture, and a limiting size of larger fragments.

As to composition:—The original drift when first deposited must have contained mostly quartzite, conglomerite and various sandstones. To this should be added, depending upon location, limestone, chert, granite, gneiss, slate, and rarely other types. Locally, any of this latter group may have been abundant, especially limestone, at any place south of the Jacoby-Paulins Kill valleys.

There are outcrops where the drift was so thin as to be soon swept away by the rain wash or where no drift was deposited. Such bedrock, too, was subject to weathering.

What sort of changes, then, did these materials suffer, because of weathering, to make them distinctly different from the Wisconsin drift composed of the same materials but only moderately affected by weathering?

Some descriptions of specific occurrences will help to bring this out.

Till.—(a) Railroad cut about three miles north of Easton. Material exposed to depth of three to five feet is compact, structureless, clayey; much of it is quite red, while part is a duller yellow-brown; no systematic distribution of color. Contains scattered fragments (maximum 1 foot) of quartzite, conglomerite, various sandstones, all of which are weathered.

(b) North part of Phillipsburg, New Jersey. Good cuts four to seven feet deep. In general looks like limestone residual soil especially since bedrock shows in several places; but is more irregularly colored—streaks and patches of darker and lighter brown in with the reddish; probably has mixed with it much residual decay from the underlying limestone; but no indication of till resting on limestone or on residual limestone soil, rather an indefinite transition and intermingling. Fragments (maximum, 3 feet) of half a dozen varieties of foreign rock are scattered through the mass, are more abundant on the surface; probably the till was originally thicker and erosion has removed a good deal of it, sweeping away the finer and concentrating the larger; fragments are almost wholly angular or subangular, are well weathered, being less tough than the fresh ones typical of the Wisconsin, and with rusty brown exteriors. Above the bedrock, in a few places, were several fragments of limestone distinctly seperated from the ledge; very much etched and quite porous, the impurities and siliceous streaks and veins stand out strongly and some of the pieces are almost nothing but a shell of impurities; the total quantity of such pieces is small and none showed on the surface.

(c) Northeast of Phillipsburg about 1½ mile. Two cuts, one four to six feet in good condition, the other eight to twelve feet deep and freshly dug (see pl. 8, A): no limestone ledge, hence the till more uniformly dark brown and less reddish; tough clayey matrix; fragments of all sizes up to 2½ feet, larger ones least common; fragments almost wholly quartzite, conglomerite and sandstones; among several hundred fragments seen, only three weathered gneiss and one large limestone (not in place); are weathered but not weak, are some shade of brown but not the deep rusty tone seen so often on surface fragments; some showed striations.

(d) Lafayette College Campus:—13-foot fresh cut, the upper four feet of which is fill. Has the dark brown (reddish) color and general appearance of residual limestone accumulation, but contains scattering foreign fragments, maximum four inches in diameter, — one crumbling gneiss, one crumbling granite that would stand handling but was very weak, another granite too much decomposed to be removed intact, a few smaller fragments of uncertain source. No limestone bedrock showing though it is known to be a short distance below.

(e) Cut at quarry of Lehigh Cement Company southwest of Martins Creek. Exposure fresh and for the most part 2 to 20 feet thick, one face 30 feet; all resting on limestone. Typical unsorted character (see pl. 8, B). Matrix compact and holds face well. Mostly uniform yellow-brown color throughout, with, however, some reddish patches and streaks. Cobbles and boulders common, both bunched and scattered, mostly subangular, maximum diameter three feet, some striated. Fragments weathered and many of them weak. Surface and upper fragments show somewhat greater weathering than those more deeply buried, though contrast is slight. Matrix has no striking difference in weathering between upper and lower positions. Upper part of limestone bedrock only moderately weathered.

Waterworn fragments are notably scarce.

No cuts are deep enough to show the depth of the weathering. There was no visible difference in this respect between the upper and lower portions of the 12-foot cut above mentioned; in the deepest cut (30 feet) there was some difference in weathering, the lower part showing less, but the difference was very moderate.

Most of the other exposures were shallow road cuts 1 to 3 feet deep. By far the greater part of the Illinoian till, like the Wisconsin, had to be judged by its surface condition as shown in fields. In both cases the fragments furnish the evidence on which judgment is based.

These then deserve some description. Literally hundreds of these were broken open for examination.

The surfaces of Illinoian fragments are commonly a fellow-brown color, which is quite in contrast with the lighter-colored, fresher-appearing Wisconsin fragments. The color very often is a rich russet tone, in other cases merely rusty, in still others a dull, dark brown. The surfaces commonly are also pitted instead of being smooth. When broken open, the fragments always show zones of color and alteration, commonly an outer yellow-brown zone merging into a duller zone within, this in turn giving way to a core of unaltered material. Many show no unaltered central portion whatsoever. The outer zone may be a mere film or as much as a quarter or half inch deep. Because the fragments vary in composition there are innumerable variations in the character and thickness of zones. Some fragments show pores where soluble or decomposable portions have been removed. Others have small spots of limonite all through them where iron-bearing particles have oxidized and hydrated. Quartzites show little or no zoning. In the rare granite or gneiss fragments, the feldspars are koalinized and the rock quite weak or even crumbling.

In fact, weakness is a general characteristic among the fragments, even of quartzites. Not that any of the quartzites are crumbling, or anywhere near so, but they have lost their customary toughness. Most of them can be broken without much difficulty, and an occasional 6-inch cobble could be broken through the center with a hand hammer. The finer textured and purer quartzites are least altered, while the coarser and more variable ones break with little difficulty.

A variation of the above mentioned conditions is important. This is the not unusual case of a fragment with a light-colored exterior which resembles very much the usual Wisconsin fragment. On breaking, this is seen to be an outer zone of leaching. This outer leached zone may be as much as 1/30 inch deep, and succeeded by the usual brown altered zone of greater width merging into a core of unaltered material. This unaltered core may be lacking and the leached zone may be thinner. The surfaces of all such fragments are pitted. In doing field work, therefore, fragments should always be broken before judgment is pronounced upon them.

The sandstones resemble the quartzites and conglomerates in all particulars of weathering. One exception should be noted,—the fine-textured, red Silurian sandstone seldom if ever shows zoning or other visible evidence of alteration; the coarser-textured ones may be spotted within.

Limestone fragments generally are lacking in the till, for solution has removed them. The rare fragments found are large and are obviously loosened from the underlying bedrock. All of them show evidence of long weathering, being porous and even cavernous or fallen apart. The impure varieties may have a zone of coherent clay an inch or two in depth which has delayed the attack on the inner portion. The surfaces are ridged and pitted as a result of differential solution and alteration.

Bedrock.—Outcrops of bedrock, because of their solidity, are not weathered so deeply as the relatively porous till. The conditions are analogous to those of the rock fragments already described. In fact identical qualities appear on outcrops of Silurian quartzite on Kittatinny Mountain. There is a leached zone, in places 1/16 inch deep, then a zone of brown altered rock ¼ to ½ inch deep, merging into the unaltered quartzite. The granite or gneiss is weakened more, has a rougher surface of differential weathering and may even be so decomposed that portions several feet beneath the surface may be dug out with the hands.

In places the roche moutonnée outlines are preserved; at other places the form is approximately retained but the bedrock has fallen apart; elsewhere the outcrop is merely an assemblage of residual blocks and fragments with a complete loss of the original roche moutonnée form. (See pl. 9, B.)

Limestone outcrops are not known over which the Illinoian glacier alone has passed and which are today exposed. All have some sort of cover. Indeed, without drift, it is believed that a cover would develop because of the susceptibility to weathering. Only one place where till rests on limestone, is known within the area mapped, viz., southwest of Martins Creek (e, page 42). Here the upper part of the limestone is weathered very little. In a few places in the Lehigh Valley the limestone is much weathered to a depth of two to eight feet below the till.

Stratified drift.—The old drift shows stratification on higher terraces and outwash remnants.

(a) The structure of a terrace half a mile east of the river at Martins Creek Station is revealed by an old gravel pit opened against the front of the terrace. A 15-foot face shows the typical stratified arrangement (see pl. 9, C), with the following divisions:—

Upper 5± feet—Medium coarse gravel with a scattering of cobbles.

Middle 5± feet—Alternation of gravel (somewhat coarse) and sand beds.

Lower 5± feet—Coarse gravel, in part with loamy matrix.

The fragments are the usual quartzite and sandstones with chert and a little slate, no limestone or pre-Cambrian rocks. There is no evidence of any great amount of decay, except the absence of limestone, granite and gneiss, and a general lack of the original toughness but there is an overtone of light brown and in the lower part a real reddish tone; the fresh appearance characteristic of the Wisconsin stratified drift is lacking. The fragments in the older parts of the exposure and on the surface above are browner. In the oversize piles a few boulders were seen among the cobbles, but none were seen in place. The top of the terrace is 140 feet above the river or 70 feet above the Wisconsin terraces at Martins Creek.

(b) Another deposit with a terrace form and plainly visible stratification is just north of Chestnut Hill on the side of a small valley tributary to the Delaware. The texture is coarse and the cross-bedding points away from the Delaware, suggesting marginal drainage which, because of ponding, may have had an outlet over what is now a low divide to the northwest. The usual characteristics of extensive weathering are present. This terrace is 180 feet above the Delaware. Part of the deposit rests on limestone bedrock well above the present valley floor.

(c) A deposit occurs in a small valley near Riegelsville, about a mile west of the Delaware. It is 90 feet above the river and is considered to be part of an overflow deposit made when the ice occupied Stouts Valley to the north. Residual waterworn boulders on the floor of the valley indicate a former large volume of water and a very active current. Weathering is pronounced. An interesting comparison is easily made between this old deposit with its absence of limestone, granite and gneiss, and the Wisconsin stratified drift, at Riegelsville near-by, with its clean, fresh appearance and usual content of limestone, granite and gneiss.

(d) An example of outwash can be seen on the north side of the tracks of the Central Railroad of New Jersey at Kennedys Station. The top is on a level with the Somerville surface. A 30-foot pit reveals limestone ledge at the bottom; limestone outcrops at the Somerville level near-by, which suggests that this is a filled sink hole. The material is not particularly coarse, being rated on the whole as gravel. (See pl. 9, D.) Extensive weathering is again well evidenced by the absence of limestone and gneiss fragments, the weakened quality, and fragments of cavernous quartz. A peculiarity is the presence of many slate fragments. In one respect this deposit is unusual; it is overlain by 3 to 7 feet of tough, clayey, brownish material containing scattered fragments of weathered quartzite and sandstone which strongly resembles till. This suggests a readvance of the ice in Illinoian time.

Summary of characteristics.—The earmarks of the Illinoian invasion, largely the result of weathering, may be summed up briefly as follows:—

The drift deposits as a whole are a deeper brown, with some reddish tone, in contrast to the lighter buff and generally fresher appearance of the Wisconsin. Also the till has a more compact, often tough, matrix.

The fragments within the matrix commonly have a brown exterior, and often possess a rich, russet, aged appearance. Many fragments have developed a light-colored exterior by leaching. The surfaces are commonly pitted. On being broken open all fragments show zones of alteration.

Only resistant rock fragments are present. Limestone is almost universally lacking. Granite and gneiss fragments are very scarce, and when present show a whitening of the feldspar and general weakening.

The resistant quartzite, conglomerite and sandstone which are so universally present, are appreciably weaker than their counterparts in the Wisconsin drift.

The outcrops of bedrock may show color zones of alteration, deep zones of decomposition or groups of residual blocks, depending on material.

DISTRIBUTION

A word or two concerning the general occurrence of the Illinoian drift is necessary. If the Wisconsin glacier did not entirely remove the Illinoian material, it should be possible to find some place where the two drifts are together—Wisconsin and Illinoian. No such occurrence has been found within the region covered by the Wisconsin glacier. The Illinoian drift is found only in that part of the area beyond (south of) the Wisconsin terminus. The southern limit is indefinite. There is no moraine of any sort. The undoubted deposits have necessarily a scattering rather than continuous occurrence for erosion has removed much of the original material. No attempt has been made to map the boundary, but sporadic occurrences of drift and scattering residual cobbles and boulders show that the glacier reached six to eight miles south of Easton. Between Easton and Allentown and north of the Lehigh River, the old drift is rather plentiful, while south of the river it is found with difficulty.

Problems

Although the distinctions between young Wisconsin and old Illinoian drift, as presented above, are valid and prevail widely, there still remain some problems.

(a) For instance, the gneiss bedrock is thoroughly decomposed to a depth of ten feet while the quartzite is weathered only an inch or so. The quartzite is more resistant but one would not expect such different results.

A companion fact is capable of more direct comparison. The cement rock southwest of Martins Creek, directly under the old drift, is only moderately weathered. By contrast, the same sort of cement rock at Cementon in the Lehigh Valley has a thoroughly weathered zone 3 to 8 feet deep between the drift and the fresh rock.

Both of the cases would have no inconsistencies if there were three instead of two glacial invasions. There would then be expected an extreme amount of weathering, a large amount (since Illinoian) and a lesser degree of weathering (since Wisconsin).

(b) Another inconsistency occurs south of Easton. The gneiss has weathered to such a degree that a combination of residual soil and rotten rock is five to ten feet deep. But small boulders of the same material moved but a short distance by the glacier are neither rotten or weak, in fact are solid enough to be used as building stone. Possibly these boulders were originally ten times as large, the decomposed rock has been removed by rain wash as rapidly as formed, and the fragment as seen today is the unaltered core, so to speak, of the originally larger piece; or possibly some rocks develop a protective rind on weathering under exposed conditions.

(c) Then there is the matter of erosion combined with weathering. Suppose a deposit of Illinoian drift 60 feet thick. Since there is a moderate difference in weathering between surface and 20-30 feet below, one can reason that at a depth of 50 feet there might be no weathering at all. If then erosion should later remove this 50 feet of drift there would remain 10 feet of drift fresh enough to be practically identical with the Wisconsin type. Possibly some misinterpretations have arisen through some such sequence of events.

(d) There remain the further questions of weathering in relation to various factors such as depth of cover, structural variation of the rock, subsurface drainage, and actual composition of the materials measured by test tube and microscope.

(e) Another problem will arise when one attempts to extend the work to the north. The comparisons made in this particular area were determined almost wholly on the conditions of the universally present Silurian quartzites, conglomerites and sandstones. North of Kittatinny Mountain these rocks naturally are lacking, the main source of drift being rock from the middle and upper Paleozoic. No true comparisons due to weathering can be accomplished without a thorough personal knowledge of the qualities of these bedrocks; which means that glacial studies should be preceded by thorough bedrock studies over a very wide territory.

Extent and distribution of the Wisconsin Glacier

(Note:—This topic is not included in the chapter on Wisconsin Glaciation because the argument is based largely on an understanding of the differences between Wisconsin and Illinoian drift. Since such comparisons have now been made it seems logical to follow them by this additional Wisconsin chapter.)

MAIN ICE SHEET

Ordinarily the extent of any continental glacier is considered to be determined by the position of its terminal moraine. In this region, the statement is commonly made that the terminal edge crossed the Delaware just below Bevidere, extending from that place westward and then northwestward to the vicinity of Ackermanville, turned northward, crossing the mountain near the "Offset," and then continued westward again. North of this boundary the whole area is considered to have been covered by ice. Thus, Lewis[1] presents such a picture, with a cross-section, showing the ice 600 feet thick on top of Kittatinny Mountain.

This hypothesis is a reasonable one, for the effects of glaciation have been found both north and south of the mountain and on the mountain itself. For the older generation of geologists no other conclusion was necessary; there was no thought of more than one glacial stage. Now that this region is considered to have had at least two stages (Illinoian[2] and Wisconsin), the theory that the ice at both stages crossed this formidable mountain needs to be tested. All writers since Lewis have accepted this general distribution for the glacier at the Wisconsin stage. The writer believes that the Wisconsin glacier not only did not cross near the "Offset" but did not cross the mountain anywhere in the area under discussion. To be specific, the Wisconsin glacier did not cross the mountain within the limits of the Delaware Water Gap quadrangle. The reasons for this belief are presented.

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[1] H. C. Lewis: Report on the terminal moraine in Pennsylvania and western New York, Pennsylvania Second Geol. Surv., Report Z (1884), pl. 1, p. 12.

[2] According to Leverett, the drift between the mountain and Easton is Illinoian, while that south of Easton is indeterminate.

The crest of the mountain is glaciated; it shows roches moutonnées and a few striæ. These latter all bear nearly due south. Both north and south of the mountain there are more striæ. These have a dominant southwest (20°-75°) direction (Fig. 10).

Salisbury[3] found no striæ on the mountain crest from the Water Gap northeast for ten or twelve miles. He found striæ within 10° of south on the high slopes north of the mountain, while on the lower slopes and the ridges (north of the mountain) the southwest directions again predominate, as they do south of the mountain. Furthermore, at a point 25 to 30 miles northeast of the Gap, his map[4] shows the direction of ice movement as paralleling the mountain and in part crossing it in a west-southwest direction. However, in the vicinity of the Water Gap this map represents the ice as moving across the mountain in a south-southwest direction.

The question at issue is this: Did a single ice sheet approach the mountain with a southwest movement, cross the mountain, moving nearly due south, and continue beyond in a southwest direction? Or were there two ice invasions, each with a different direction of movement and distribution? The writer believes that the latter is the true interpretation.

On the basis of striæ alone no convincing case could be made. The sharp contrast of direction of striæ on mountain and valley need not mean two advances of the ice. It is an established fact that prominent valleys modify the regional movements of continental ice, so it might be expected that the prevailing northeast-southwest trend of the Great Valley would divert the general southward trend of the ice. One would expect, however, that this trend could not assert itself at once. That is, ice moving southward over the crest of the mountain should keep its direction near the mountain and feel the valley influence more strongly out in the valley itself. This is contrary to fact, for the striæ bearing most strongly southwest are the ones nearest the mountain (Fig. 10).

It is on another count that the best evidence for the two-stage interpretation rests. As both the Illinoian and the Wisconsin sheets have overridden essentially the same rock terrains, they should have gathered and distributed essentially similar materials. Yet the two drifts today are not identical. The fundamental factor responsible for this lack of identity is differential weathering. The Illinoian drift, being much older, shows effects of a long period of weathering; the Wisconsin drift is distinctly fresher.

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[3] R. D. Salisbury (and others), The glacial geology of New Jersey: N. J. Geol. Surv., final rept. 5 (1902), 802 pages.

[4] Op. cit., pl. 8.

Earmarks of the earlier Illinoian glaciation, the result of weathering are summed up on page 46.

The Shawangunk quartzite, of which Kittatinny Mountain is composed, is a dense, tough, resistant rock. Fragments of it make up a large proportion of the drift to the south. On the mountain this resistant rock has retained striæ at not more than half a dozen places along ten miles of crest. The striæ so far recognized are faint rather than clear cut, which is to be expected in so hard a rock. There are many roches moutonnées (See pl. 9, A), but while preserving their form they have lost their freshness and show no striæ. Some are merely assemblages of loosened blocks. There are long stretches where completely separated, residual blocks are the rule. Furthermore, the rocks with striæ, as well as the roches moutonnées without them, have prominent zones, and commonly rinds, of weathering. This is because the Shawangunk, while definitely a quartzite, is impure enough to yield color zones on weathering. The normal dark gray may, on the exterior portions, be leached to a light gray, nearly white.

Contrast with this the conditions in the outcrops south of the mountain. The bedrock here is slate and limestone. Neither of these is very resistant to weathering, the limestone being susceptible to solution. Yet outcrops of these rocks show well-defined, sharp striæ and smoother, cleaner roches moutonnées. It is recognized that degree of exposure and variation of structure influence the rate of weathering, but with due consideration given to these influences it still is inconsistent to expect the resistant quartzite to weather more in a given time than the much less resistant limestone and slate. Comparison can be made directly between quartzite and quartzite. The Wisconsin drift contains many fragments of Shawangunk quartzite; yet one can pick from the surface of the drift hundreds of these with no rind of weathering. It is unreasonable to expect exposed fragments of rock not to weather and yet to expect the same rock in an outcrop a mile away to weather deeply during the same time.

Inconsistencies of both striæ and weathering are answered with the explanation that (a) the mountain crest was overridden by the Illinoian glacier; (b) ever since the withdrawal of the Illinoian ice the mountain crest has been subject to weathering (a time long enough to affect even tough quartzite); (c) the Wisconsin glacier crossed the mountain well to the east of this area and moved southwest into this area as two lobes, one on each side of the mountain. This seems to be a more reasonable explanation for existing facts.

The exact place where the Wisconsin glacier crossed the mountain has not been determined. It is well out of the quadrangle, at least ten miles northeast of the Water Gap.

The terminal moraine west of Bangor has the characteristic knob and kettle topography. This extends north to the foot of the mountain, then curves northeast, following the base of the mountain for several miles. It does not cross the mountain within the limits of the map. There is no topographic expression of a moraine on the crest, although there is good opportunity for its preservation on the wide crest of the "Little Offset," if it had ever existed there. None of the drift on the crest is fresh like that of the Wisconsin age. All this confirms the other evidence cited.

Another minor confirmatory item is the general absence of extremely large Shawangunk erratics. If the Wisconsin glacier had come directly across the mountain, it could have secured many talus blocks to distribute over the valley: but moving as it did, its collecting area was more restricted.

ICE TONGUE

There is a further modification of the older view concerning the distribution of the Wisconsin glacier. Instead of an ice front athwart the Delaware River, just below Belvedere (Fig. 10), the writer postulates an ice tongue which extended down the valley, having a blunt tapering form for the first three miles below the old position assigned to the terminal moraine, then a twelve-mile reach down the narrow Delaware trench.

Till occurs well above the area of stratified drift in the valley, below the so-called terminal moraine of the earlier writers. It combines characteristics of both Illinoian and Wisconsin drift, which means that the two types of till are mixed. The mixture could have been made only by the Wisconsin glacier bringing fresh material and incorporating it with the older, more weathered Illinoian debris. In other words, the Wisconsin glacier occupied the limestone lowland for some three miles below the so-called moraine, tapering down to the Delaware trench proper, near Martins Creek.

In an earlier article the writer[5] presented the evidence of this ice tongue in the Delaware Valley. Briefly, the points made in that article are:

(1) Wisconsin till occurs beneath Wisconsin stratified drift at Carpentersville (Pl. 10).

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[5] Freeman Ward, A Wisconsin ice tongue in the Delaware Valley: Am. Jour. Sci., 5th ser., vol. 18 (1929), p. 446-448.

(2) Till resting on unconsolidated material suggests thinness of ice.

(3) The valley has a flat rock bottom and limestone cliff sides. The till has the typical characteristics—(a) lack of structure, which is quite in contrast with the stratified drift resting upon it; (b) assortment of sizes of material from the sandy loam of the matrix to boulders; (c) compactness—it is harder to shovel and stands up better than the stratified drift; (d) an occasional striated fragment.

The till known to occur at this locality (Carpentersville) is about 20 feet thick over an area about 50 by 100 yards. Although it is probably absent from parts of the pit, there is scarcely any doubt that the extent is much greater than indicated by the above figures. The overlying stratified drift is about 25 feet thick.

The till is not especially weathered, and contains frequent fragments of limestone and gneiss. In other words, it has the qualities of Wisconsin, rather than older, till. It seems unreasonable to say that it is a remnant of old drift lacking weathering because of its depth of burial. By comparison, a deposit of stratified drift about 3½ miles east, reported as old drift by Leverett, is 30 feet thick, is exposed from top to bottom; yet it shows no accumulation of limestone and gneiss or any other evidence that weathering in its lower parts has been much limited. It should be remembered, too, that all the older till was subject to much weathering before any protective cover of Wisconsin drift could be deposited.

Additional favorable arguments are—(a) Upstream, a short distance from the till, there is a deposit of fine material having a structure that may well be called varves. Instead of the ordinary sand and coarse gravel, so common in the terraces, it is made of alternating fine sand and silty fine sand (about 20 pairs per foot) with a short thin lens of gravel near the top. Such a formation would scarcely mean deposition from a freely moving river; rather, it suggests a ponding of the river water. This, in turn, strongly suggests ice as the agent of ponding. Judged on the basis of weathering, this deposit also is of Wisconsin, rather than Illinoian, age. (b) If the valley train, now represented by its remnants, the terraces, was laid down while the ice front was at Belvedere, it is not to be expected that the texture should be alike all the way down. The rush of water from the ice front should slacken progressively down-stream. The deposits at Martins Creek and at Carpentersville are about eleven miles apart, yet the textures of the two are nearly identical. Half way between these two (at the Steckel pit) the deposit has the same texture. Nor is there a progressive coarsening of texture above Martins Creek. This similarity of texture, on the other hand, is accounted for by assuming an ice tongue receding progressively and so furnishing a more nearly uniform current throughout the twelve miles of its withdrawal.

Some may think that a tongue, 12 miles long and ½ to ¾ mile wide, has no precedent. However, such a thing is not impossible, and without this it is extremely difficult to account for the several facts cited. In this connection, data may be presented concerning several Alaskan glaciers:—Crescent Glacier is six miles long and ½ to ¾ mile wide; a narrow valley, formerly occupied, extends 1½ miles farther. Serpentine Glacier is 7½ miles long and ¾ mile wide. Heney Glacier is about 16 miles long and one mile wide. Nebesna Glacier is 55 miles long and 2½ miles wide—all of which suggests that a glacier 12 miles long and ½ to ¾ mile wide is not an impossibility.

EVALUATION OF PREGLACIAL, GLACIAL, AND POSTGLACIAL EROSION

It should be clearly evident that the present condition of the Delaware Valley region is not the result of one process or operation. The region has had a lengthy history and the forces that shaped it have left overlapping, incomplete records of the whole series of happenings. This interesting complex of preglacial, glacial, and postglacial events constitutes the problem of this paper.

The dominant active force in forming the topography and in bringing it to the present condition is erosion. First an indefinite period of erosion by running water, then an interruption while glacial ice was the controlling agent; following this, running water again ascendant. The interrupting glacier is the fulcrum about which the lever of erosion swings. The expression of erosion is the topography which it carves. We think, then, in terms of preglacial, glacial, and postglacial topography.

Criteria for Evaluation of Preglacial Topography

1. Comparison of glacial with extra-glacial topography:—
   Especially where the two are reasonably near each other and the bedrock materials and structure are similar.
2. Bedrock topography must have been similar to that:—
   - (a) Which today is striated or has roche moutonnée—Nearer the terminus the similarity should be close, for the ice was thinner and erosion less: well back from the terminus less correspondence, but large extremes of difference unlikely except locally.
   - (b) Which today has a mantle of till. (Same qualifications as in 1.)
   - (c) Which is buried by stratified drift—revealed by cuts and wells. However, this must be interpreted with certain allowances. Much stratified

drift, especially that found along the main drainage arteries, is probably not resting on the exact preglacial surface of that locality. With abundant melt-water and free pathway the natural result should be erosion in advance of deposition. And where excessive drainage from the glacier is unhampered and the gradient good, there may be very considerable deepening of the channel before overloading and deposition can occur.

3. In prominent valleys:—
    - (a) As indicated in 2(c) above, run-off from melt-water can be expected to erode deeply. Re-advance of ice may produce striæ well below original preglacial level.
    - (b) Rock terraces and shoulders suggest position of preglacial valley floors.
4. Modified drainage:—
    - (a) Right-angled or obtuse tributaries.
    - (b) Youthful portions of otherwise mature or old valleys.
    - (c) Buried channels not now occupied.
    - (d) Lakes and swamps.
    - (e) Reversed drainage.

1. *Topography.* There is no sharp contrast between glaciated and non-glaciated topography, nor between the topography of the areas of Wisconsin and Illinoian glaciation except locally where there is a small stretch of terminal moraine (Wisconsin) or a group of kames. Otherwise one could travel across the whole length and breadth of the area, and beyond, and not (from the topography alone) think of the region as being glaciated. In fact, careful search must be made to determine much of the boundary of the Wisconsin ice. A generation ago geologists did not even know there was Illinoian glaciation here, and even now its limits cannot be given with precision. It should be noted, too, that all the limits of the Illinoian and all but about four miles of the Wisconsin boundary in this region have been determined without the aid, and in spite of the absence, of glacial topography. There is no question, then, but that the major topographic features of the area are all preglacial:—the "peneplanes," monadnocks, the prominent mountain, the Great Valley, the main courses of the Delaware, Lehigh and other large streams, were formed before the advent of the great ice sheets.

The details of these happenings belong to the essential history of the "peneplanes" themselves down to and including the Somerville, and so do not properly belong in this paper. The erosion that concerns us is very evident, youthful post-Somerville trenching.

2. (a) *Illinoian striae.*—The only bedrock that shows Illinoian striae is that on the crest and upper slopes of the mountain. This mountain, then, had a higher crest before the glacier arrived. How

much has been removed is not known. Lesley[1] estimated that 70 feet had been eroded by the ice, albeit he and his generation knew no distinction between Illinoian and Wisconsin glaciers in eastern Pennsylvania. Salisbury[2] estimates a few feet, though he too considered it the work of the combined glaciers. Very likely the crest profile was less smooth in pre-Illinoian time than now, though the peneplane history of the region precludes any saw-tooth or serrated outline.

2. (a) *Wisconsin striae.*—In the Great Valley area south of the mountain only about a dozen outcrops with striae have been seen. These are all on the upper parts or crests of the Harrisburg and Somerville surfaces.

North of the mountain the striae are more abundant, largely because the rock is of better quality for taking and preserving them, partly because the narrow, steep ridges have, by more rapid removal of the drift, allowed greater exposure, and so observation, of the bedrock. The striae occur mostly on the crests or upper slopes, but a few were seen on the lower slopes, none on the valley floors.

The evidence from the striae indicates that both the major and intermediate relief in preglacial time were very similar to that of today. But as to the minor relief of gully and deep trench they give no information, except in the one case of the Water Gap. A short distance south of the Kittatinny Hotel horizontal striae occur on a small cliff along and above the road and also along the railroad below. Similar ones are reported on the New Jersey side. The forming of high terraces just south of the Water Gap requires a readvance of the ice, hence it cannot be said that the gorge of the Gap as we see it today, was completed before the first approach of the Wisconsin glacier.

Where striæ are lacking, roche moutonnée give similar information. These parallel the striae and are largely on the crests or upper slopes.

The evidence of striae is conclusive as regards the major and intermediate relief. In these respects the preglacial topography was similar to that of today. It would not be identical for the divides and ridges must have been higher. Each glacier probably removed 5 to 50 feet of bedrock, except close to the terminal region. The striae give no information as to the date of the deeper trenching.

2. (b) *Till mantle.*—Both Wisconsin and Illinoian till occur widely on the crests and lower undulations of the Somerville surface; they are found also on the Harrisburg surface. None was seen on any

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[1] Lesley, J. P., Pennsylvania Second Geological Survey, Rpt. Z.
[2] Salisbury, R. D., Geological Survey of New Jersey, vol. V, 1902, p. 70.

prominent valley bottom, but there is little chance to do so. It is possible that till occurs on the floors of minor valleys, but if so there are no cuts to prove that the deposit may not have been wash.

The evidence from till, then, is the same as from the striae.

One occurrence applies to the pre-Illinoian topography. This is the presence of till in the valley of the Lehigh River, in a fresh cut a little south of Catasauqua. The till is definitely within the valley proper but well above the present valley floor, slightly above the highway which runs along the terrace. The cut was not deep enough to show all the relationships but the conditions pointed to a broad and shallow pre-Illinoian valley.

2. (c) *Stratified drift.*—The occurrences of stratified drift are confined to the Delaware Valley and its main tributaries, and as stated under "Criteria" (2c) must be used with some judgment. Most such deposits are of terrace type already discussed. The amount of erosion preceding deposition may have been considerable, hence these valleys as receptacles for stratified drift may have been highly modified from their preglacial character.

The Illinoian stratified drift has more meaning. Along the Delaware the few authentic occurrences found were all well up on the valley walls, resting on rock 90-140 feet above the present level of the river. This strongly indicates that there has been a post-Illinoian deepening of that amount.

Since melt-water may erode before deposition, the surface on which the Illinoian stratified drift rests may be lower than the original pre-Illinoian surface at that point.

An important point to keep in mind also is the fact that the texture of these deposits is less coarse than that of the Wisconsin stratified drift which occurs in the same valley but at a lower level. The lesser velocity indicated can well mean that the terrain as a whole was lower, hence had more moderate slopes with less vigorous streams.

3. (b) *Rock terraces and shoulders.*—The immediate valley of the Delaware is young in form and distinctly incised below a former mature or early old age topography. This is made apparent in many places by the topographic unconformity or two-cycle cross profile in which rock shoulders (S, fig. 9; also see fig. 7, A, D, F, H, I) and some rock terraces mark the position of the older valley floors. Similar trenching is apparent in the valleys throughout the region. In other words this is the well

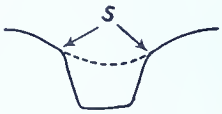


Figure 9. Cross-section of valley showing rock shoulders.

known post-Somerville erosion. The amount ranges from not less than 150 feet near Water Gap to about 100 feet in the Easton region. Throughout most of the region the present streams are flowing on valley fill, the depth of which is known in only two places. It extends 50 feet below river level at Delaware and 15 feet at Carpentersville. The depth of this fill must be added to give the total amount of trenching. The vertical amount of this erosion, then, is 115-200 feet.

Although this erosion is definitely post-Somerville, is it also post-Wisconsin? The Wisconsin stratified drift occupies the Delaware and tributaries, so the erosion must have been accomplished before the stratified drift was deposited. The position of the Illinoian stratified drift as noted in 2(c), above, means that the trenching was post-Illinoian. The writer believes that the major cutting was accomplished during Wisconsin time, chiefly during the early period of recession, and of course immediately preceding deposition of the Wisconsin stratified drift. The reasons for this are better brought out in the following pages.

4. *Modified drainage.*—This is not a region where drainage modification is striking and obvious. There are scarcely any lakes. Swampy tracts are not particularly common, and most of them are small. Nor are there any strong contrasts in the stage of development in any valley. Also there is some doubt as to the presence of any buried channels.

Yet there are certain qualities of the drainage of the Water Gap area that depend on glaciation and certain conditions that are best explained by an adjustment to glacier presence and withdrawal. Reference to Figure 4 will bring to notice several facts. The stream pattern is strongly dependent on the dominant N.E.-S.W. structure, except in the area south of the mountain and west of the Delaware. In this latter area the streams, except Jacoby Creek, tend to cross the structure. Notice the right-angled or reverse positions of the headwaters of Martins Creek. For instance, the tributary W starts flowing nearly east, then abruptly turns southwest. The larger tributary to the east does the same. The small tributary Z starts flowing a little east of north, then turns abruptly to the northwest, then to the southwest; a companion tributary just to the west of Z behaves similarly. We have, too, the right-angled tributaries to the upper part of Allegheny Creek. Similar cases may be found at several localities both east and west of the Delaware. In other words, the regularity of the pre-Wisconsin streams has been interrupted, new divides established, former divides cut down. The probable former

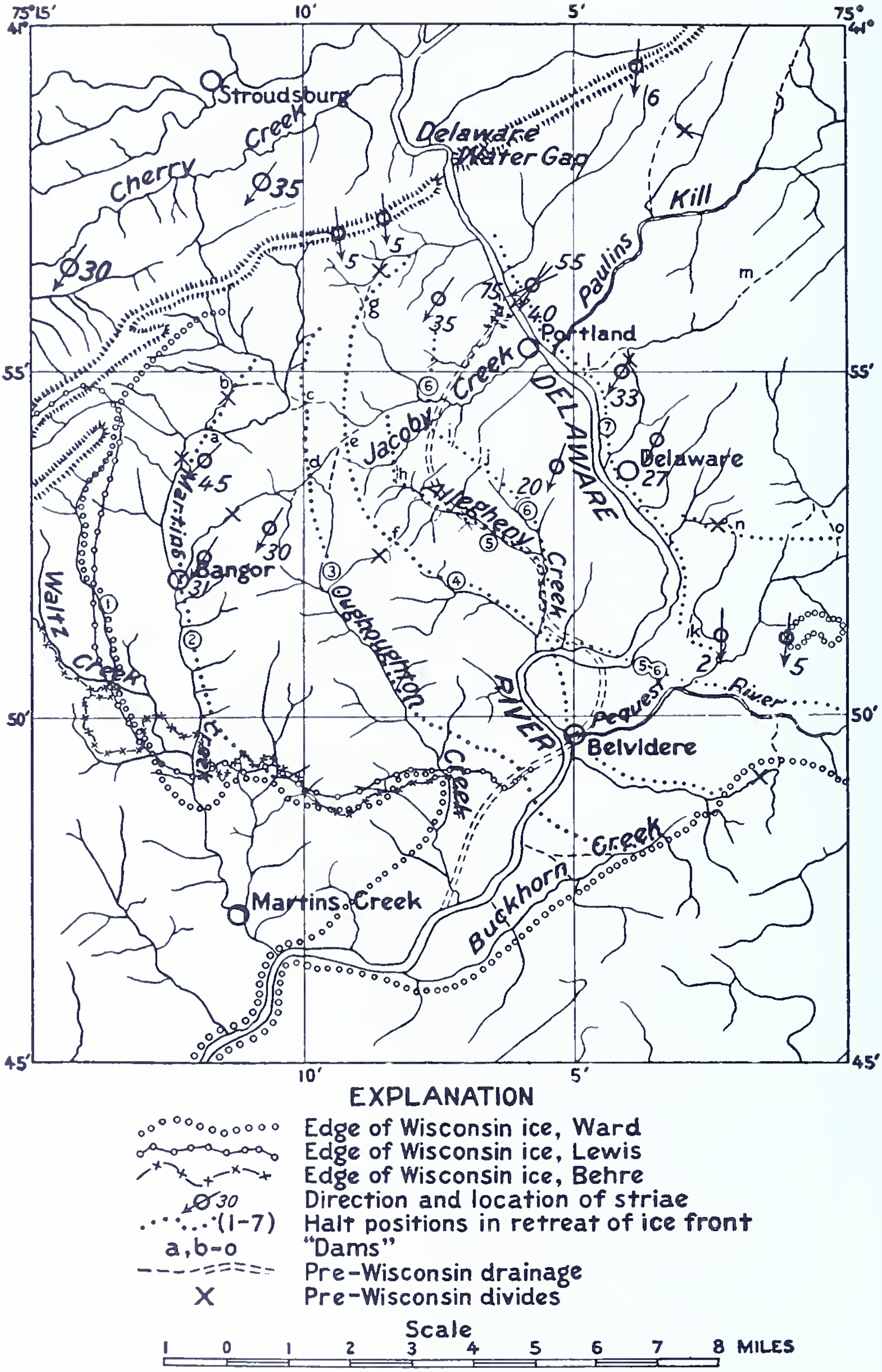


Figure 10. Map showing edge of Wisconsin ice, halt positions, and striae.

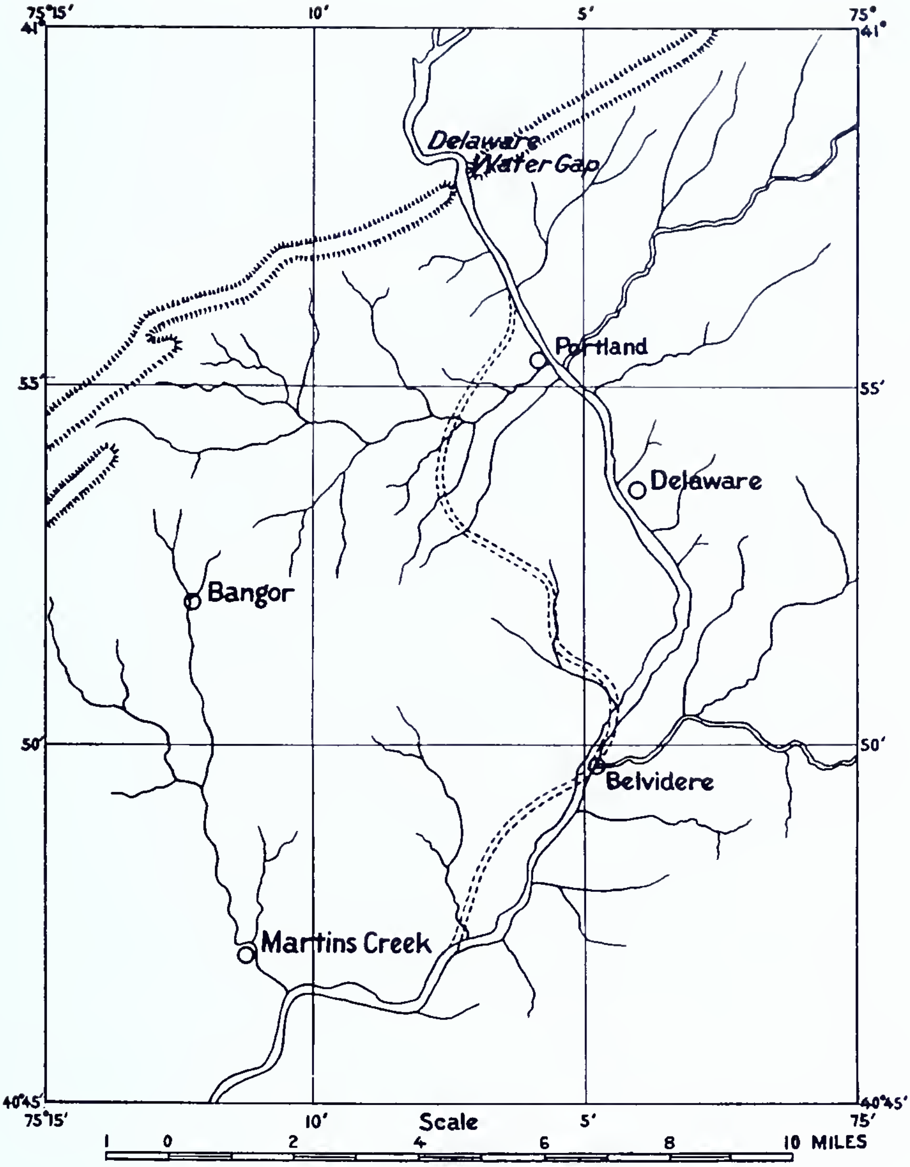


Figure 11. Pre-Wisconsin drainage and present river.

continuities and divides of this pre-Wisconsin regular stream system are shown in Figure 10. Terminal edge of the Wisconsin ice is also marked in its maximum extension. From this is constructed the probable pre-Wisconsin drainage shown in Figure 11. The drainage in the uplands at the extreme southeast, as well as that north of the mountain is not attempted.

Several other facts should be in mind before the development of the present from the pre-Wisconsin conditions is discussed:—(a) The terminus of the Wisconsin glacier is marked by a recognizable moraine only on the west, north from the crossing of Waltz Creek. Throughout the remainder of the terminal position the topographic expression of the phenomenon has been removed. (b) As noted in 3(b) above, the Delaware and smaller streams have suffered a definite trenching in post-Illinoian time. (c) Bedrock outcrops freely in the low hills of Paulins Kill valley, but in its counterpart (Jacoby Creek valley) on the Pennsylvania side of the Delaware, such outcrops are lacking.

It is believed that the advancing glacier accomplished only a moderate amount of erosion partly because the early old age topography which the Wisconsin glacier encountered offered few contrasts to levelling, partly because the glacier was not an especially effective tool (since it was not thick enough to override the mountain, and it was nearing its terminus), and partly because the changes noted can be explained in another manner, as follows:—

After the ice reached its maximum extent and began to recede three processes were at work:—1. the forming of dams of drift at certain places; 2. active, strong erosion by melt-water, especially along the margin; 3. a progressive elevation of the land as a whole. The recession was towards the northeast rather than north; that is, the rate of depletion was greater along the west and southwest than the south edge of the lobe. The recession was not uniform. There were halts when the supply of ice was sufficiently great to maintain the ice edge at a given position for a geological moment of time, but not enough to develop a recessional moraine, although some dams were built. Perhaps "dams" is not the best word to use. In a few places excessive drift is visible today; in others it is not so apparent. At least there were stoppages of some sort: in part thick drift as a true dam, in part ice blocks and moderate drift, and in part no doubt merely the ice front athwart the drainage lines. The "dams" are indicated on Figure 10. With no great new supplies of ice being furnished, the total recession did not take long, geologically.

At each halt position certain modifications of the pre-Wisconsin topography were effected, resulting finally in the present topography and drainage.

At position 1 (Fig. 10), the melt-water concentrated along the margin of the ice and flowed south because of the regional slope, thus forming the valley along which the small unnamed stream flows between Martins and Waltz Creeks.

At position 2, Martins Creek was incised by a similar flow along the ice margin. Furthermore, "dams" a and b in two of the eastward flowing streams, combined with the marginal drainage, allowed Martins Creek to extend headward by capture.

At position 3, marginal drainage established Oughoughton Creek. The "dam" at d ponded the water till it overflowed the divide at the southwest, cutting the narrows northeast of Bangor, thus adding more to the headwaters of Martins Creek. The marginal drainage held by the ice and "dam" c could not flow south because of the slate ridge between c and d. The accumulated water could more easily sweep away the weak "dam" a, allowing the important west fork of Martins Creek to come into being.

During these three shifts of position the drainage along the southern edge of the ice was unrestrained. Because of the southeasterly regional slope there would be no concentration of waters along the southern margin of the ice. In contrast, there would be a steady outpouring of melt-water along the whole southern front and across the morainal material. In this way the terminal moraine as a topographic feature would be obliterated.

Halt position 3 is also responsible for the quasi-morainal topography usually considered the terminal position in the Delaware Valley just below Belvidere.

At position 4, besides the two minor changes at f and g, there was another and final addition to the headwaters of Martins Creek,—the "dam" at e would add one more portion to the tributary which joins the creek at Bangor. A still more important change was the development of the west tributary of Allegheny Creek and an extension of this deep incision south to Belvidere along the margin of the ice.

During these four sets of changes the ice margins south and southeast of Belvidere would integrate the various cross streams into the single southwest-flowing Buckhorn Creek. The excessive marginal drainage here may also be responsible for the very steep margin of the Highlands.

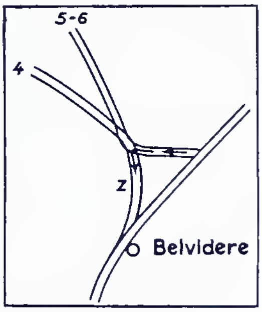


Figure 12. Delaware River channels at Belvidere.

Positions 5 and 6 would, by the incision of marginal drainage and the dams at i and j, complete the formation of Allegheny Creek and its right-angled tributaries. Another important act was the initiation of the curve of the Delaware just above Belvidere. One must remember that the land as a whole was rising and so the depth of the Delaware still under the ice was some 150 feet less than today. In the accompanying sketch (Fig. 12), channel Z, initiated in position 4, was accentuated by the marginal drainage in positions 5 and 6, so the water would naturally flow in the longer deeper path (shown by the arrows) rather than in the shorter shallower and more direct original route.

Positions 5 and 6 are also responsible for the morainal dam which blocked a good-sized valley to make Green Pond (Mountain Lake) just to the east of this area.

Position 7 marks the time of the main deepening of the Delaware. The melt-water had a straight sweep along the margin and down the regional slope. Furthermore, not only was this melt-water derived from the ice south of the mountain, but the ice had withdrawn far enough so that the Water Gap was cleared, and thus allowed passageway for melt-water from the lobe north of the mountain. This mighty flow incised the valley floor to its maximum extent and set the tributaries at work cutting their channels to grade.

Further withdrawal produced minor changes at m, n, 1, and o, which adjustments are simple enough to be self evident.

In the recession from 6 to 7 and to some extent in the early phase of 7, the stagnant ice blocks left in the low Jacoby Valley were buried by very coarse outwash spread by very swift currents which had no escape elsewhere. This deposit, on the melting of the blocks, became the kames which are now so prominent in that valley.

On the recession of the ice northeast up Paulins Kill valley, the waters, with the deep Delaware trench to empty into, found it easy to sweep much of the loose material from the rock surface. Only where stranded blocks or larger ice masses slowed up the currents were loose materials entangled and deposited. Thus it is that rock outcrops are plentiful there and a trench for the Kill itself. The Pequest has had an analogous experience.

The above statement of sequences and consequences seems reasonable in that it gives a connected explanation for an assemblage of facts:—(a) Preservation of morainal topography one place and its removal in others, (b) the courses of various creeks which are roughly concentric with the moraine and across the structure, (c) the reversed and right-angled tributaries, (d) the lack of outcrops in Jacoby Creek valley and the presence of outcrops in the companion Paulin Kill valley, (e) the trenching of the Delaware and its tributaries, (f) the deeper condition of the Delaware north of Belvidere. (g) Another fact, not so far suggested, fits in. The amount of cutting of the Delaware below the Harrisburg level, measured just south of Water Gap, is not less than 170 feet greater than the similar cutting of the Lehigh below the Harrisburg level just south of Lehigh Gap. The two gaps are also that much different in depth. The active melt-water and the progressive uplift assumed would be expected to produce this one more effect.

The depositional story is to be superimposed on this general plan. In the smaller tributaries there is abundant wash from the unprotected slopes. In the Delaware and main tributaries, deposition was closely subsequent to the trenching. This part of the story is presented in detail in another chapter. Some of the tributaries suggest that they are a type of hanging valley or would be if uplift should sweep out the fill and allow the Delaware to flow at the bottom of its trench. (They are hanging valleys, but the greater deepening of the main valley has been accomplished by water rather than by ice erosion.) This means that the deposition did follow the trenching quickly, so quickly in fact that complete accordance of the tributaries was not possible.

Summary.—The pre-Illinoian topography was one of moderate relief. The streams moved in relatively shallow broad-bottomed valleys in positions and on a type of topography indicated by the present remnants of the several "peneplanes," which of course are preglacial. The terrain was in early old age, and as a whole lower and nearer base level than now. The Delaware flowed at a position somewhat above the present rock shoulders and terraces. We would expect that it should have had a more meandering course than today. The prominent curve of the high valley walls way from the present channel about a mile north of Portland suggests where the first turn south of the Gap started. A possible course is shown by dotted lines in Figure 11. The evidence for this is not convincing, but cannot be ignored. Another small item fits in with this idea of an early old age topography over which the Illinoian glacier moved. This is the absence of large erratics of quartzite in the drift. If the southern face of the mountain had been as today a cliff with steep talus made of many very large blocks, there would have been ample opportunity to collect and distribute these blocks as large erratics. On the other hand with no prominent cliff and a well developed and well-weathered talus, opportunity for receiving large blocks would be more limited.

The overriding by the Illinoian glacier probably subdued the topography still more both by erosion and deposition of till. On recession, it is believed that there was erosion by melt-water in advance of the deposition of stratified drift, as has been described for the Wisconsin recession, but to a lesser degree. In the Lehigh Valley and in one case in the Wind Gap quadrangle, Illinoian drift rests upon rock floors cut below the early old age profile assumed and in part shown by rock shoulders above. Younger trenching reaches well below these rock floors (now terraces). Other supporting instances could probably be found by further search in the Wind Gap and Allentown quadrangles.

The Wisconsin glacier found the terrain approximately at the level maintained previously, and reached the limits indicated. Erosion was probably moderate, for the reasons already given on page 60. Because of its prominence in line with the southwest ice advance, the limestone lowland in the Paulins-Jacoby tract may have suffered more ice erosion than the other parts of the area. On recession, the active melt-water erosion, combined with a progressive uplift, produced the trenching which is so prominent a feature of the landscape and which is described in detail above.

Post-Wisconsin erosion has accentuated this, has also cut away and terraced much of the stratified drift, has removed much of the till, and has produced the minor details of channelling on all slopes; also, many minor tributaries, stimulated by the deepening of the mains, have grown headward, resulting in some modification by capture. The big bend of the Delaware just above Belvidere, initiated during recession, has migrated until it has the sharp curvature of today.

Glacial striae, weathering, erosion and time.—It may be questioned whether glacial striæ can withstand the elements for any great length of time. To be specific,—is it possible that glacial striæ on the crest of Kittatinny Mountain could have been preserved from Illinoian or pre-Wisconsin time? A recapitulation of the evidence will make an answer more readily understood.

The point already made is that there were two advances of the ice instead of one and that the paths followed in each case were different, the first and older one moving toward the south directly over the mountain while the second or younger one moved toward the southwest on both sides of the mountain, leaving its crest untouched. The very striking difference in striæ fit into this interpretation as do the difference in weathering.

Now as to this latter, the weathering on the limestone and slate of the valley is not as deep as that on the quartzite of the mountain crest. The drift in the valley is only moderately weathered, the drift on the mountain is well weathered. The topography of the valley still retains (west of Bangor) the knob and kettle morainal characteristics; this moraine fronts a drift-covered area with gently undulating topography lacking knob and kettle, and uniformly showing extensive weathering. These contrasts in bedrock, drift, and topography, combined with the direction of the striæ in each area seem convincingly to prove the two ice advances. The last one has been accepted as Wisconsin, the first one is called Illinoian because Leverett so named it.

Some comments on weathering and erosion are pertinent. (1) The Silurian rock is extremely tough and insoluble. In the outcrop on the mountain, where striæ still exist, the color changes are as deep as in fragments of the same quartzite found in the old drift. If the fragment, open to attack on all sides, could retain its integrity, much more so could the bedrock. The fact is the weathering is similar in each. (2) Mechanical weathering can be active only where the rock has cracks or small pores. The fragments in the old drift lack these cracks and are intact as far as shape or rupture goes. On the mountain the striæ appear only where the bedrock is massive; adjoining these may be a jumble of residual fragments representing a former outcrop which can be assumed, originally, to have contained more cracks. There is almost no material in the quartzites to produce volume change by hydration. (3) If the drift cover were retained, both chemical and mechanical weathering would be retarded. It is more than possible that the mountain originally was broader. We can think of the former extent of the Silurian not as a projection of the dip seen today in the mountain (as in Fig. 13, A) but as a diminishing dip originally part of a broad fold and so nearly horizontal for a quarter of a mile, say, south of the present mountain (as in B). Under this concept there would still be enough left, before the advance of the older ice, to give to the mountain a broad top instead of the present narrow crest. This would serve as a better collecting area for drift. After the withdrawal of the older ice this drift cover would tend to remain because erosion would be almost nil on this broad mountain. Until the front of the escarpment worked back erosion would not tap the cover. All during the last advance of the ice this broad mountain, standing above the glacier, would be little changed, because the continuous cold would hold chemical weathering dormant and would for a similar reason reduce the action of running water to a minimum, thus cooperating with the low gradient of the mountain top, while the cover would prevent the usual frost weathering. But the gnawing ice would be reducing the width of the mountain by attack along its sides. By the time the last ice had withdrawn the

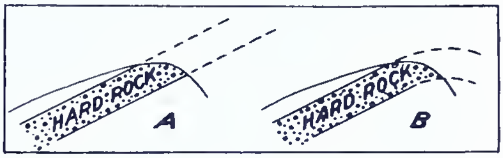
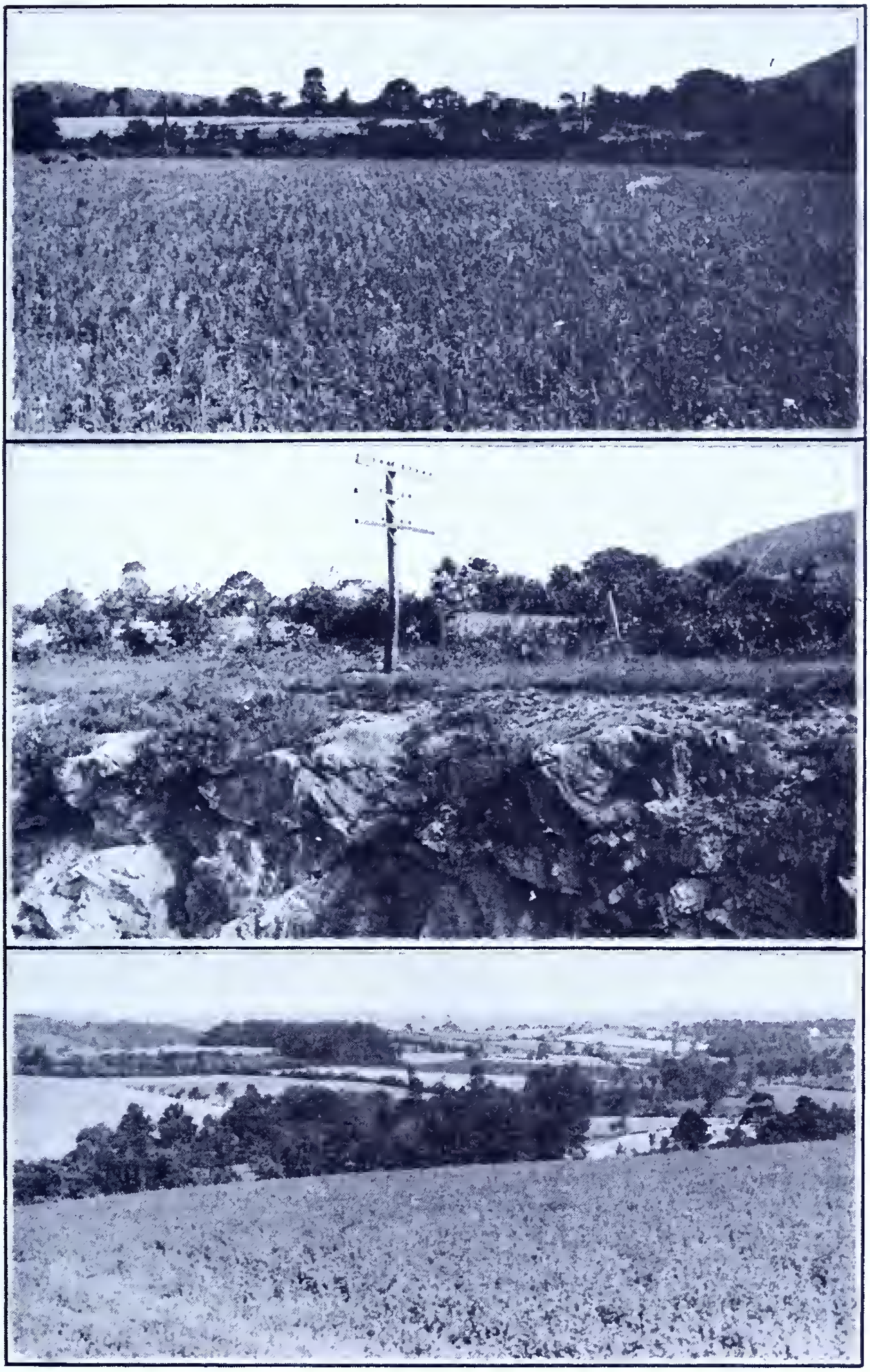


Figure 13. Cross-section of Kittatinny Mountain.

width of the mountain had been reduced so that erosion could finish the job in post-Wisconsin time. In the latter part of the interval the cover was removed and the present conditions soon produced. So it is that tough insoluble rock, wider crest, cover, and the retarding influence by continuous cold were responsible for the limited amount of weathering and erosion.

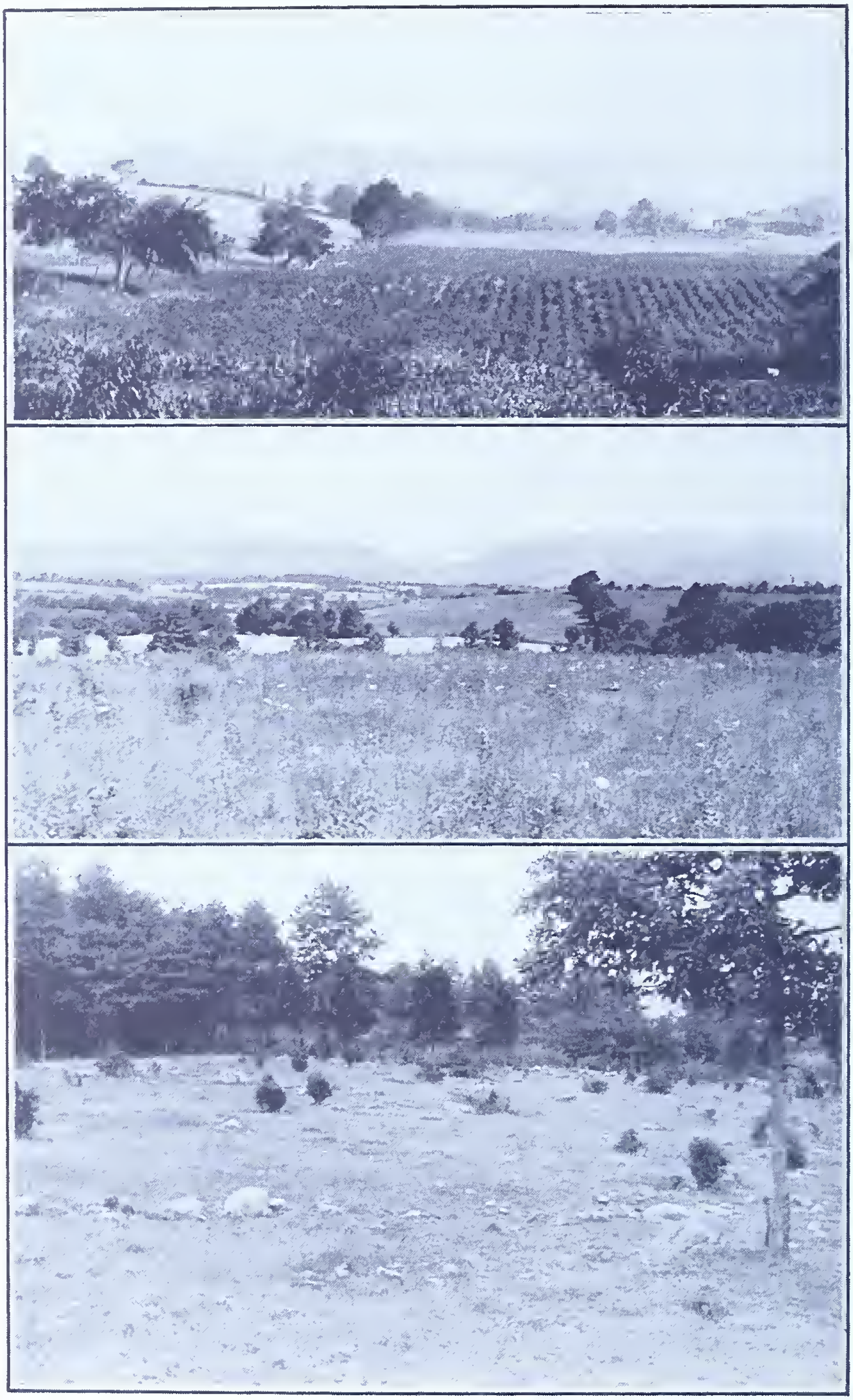
I do not see how we can get away from the fact of two ice advances separated by some time interval. Whether this interval was as long as between Illinoian and Wisconsin may be questioned. It is possible that the two ice advances and interglacial period were all Wisconsin.

PLATE 1



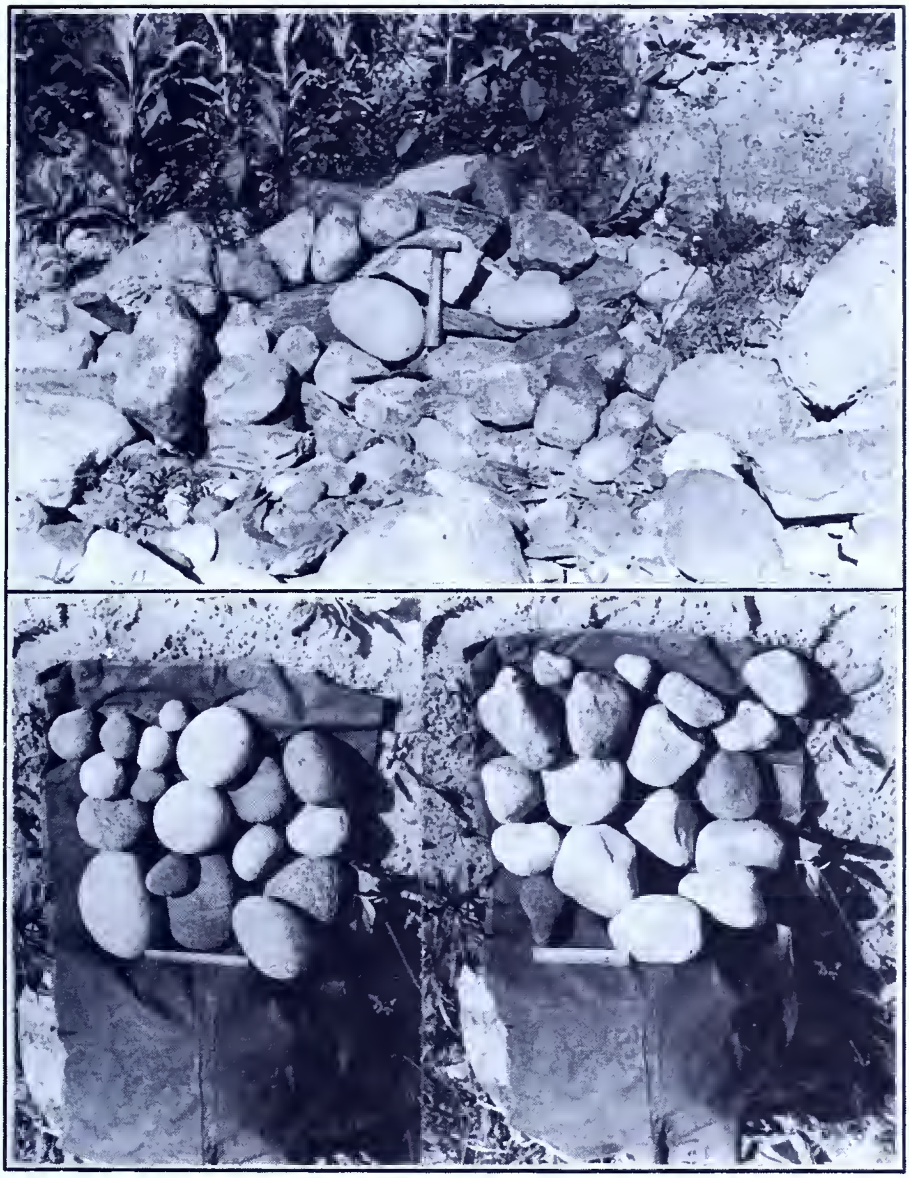
A. Terrace near Belvidere.
B. Bedrock exposed in railroad cut shown in A.
C. Typical slate belt landscape.

PLATE 2



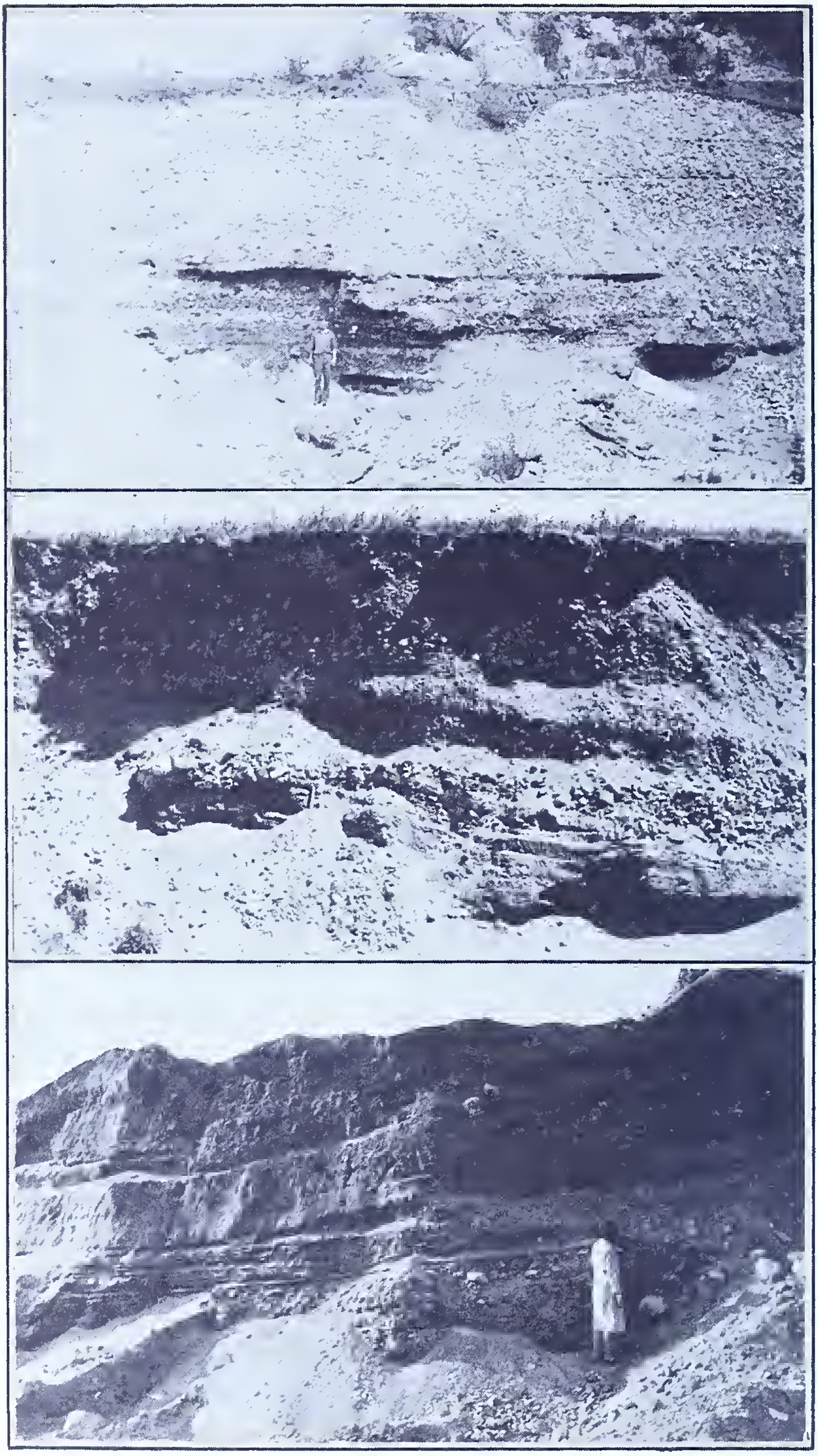
A. Typical slate belt landscape.
B. Delaware Water Gap from southeast.
C. Stony till surface east of Belvidere.

PLATE 3



A. Waterworn and angular rocks from Wisconsin till.
B. Rounded stones from Jacoby kames.
C. Subangular stones from Jacoby kames.

PLATE 4



Wisconsin stratified drift
Upper, Riegelsville; middle, south of Belvidere;
lower, Jacoby kames

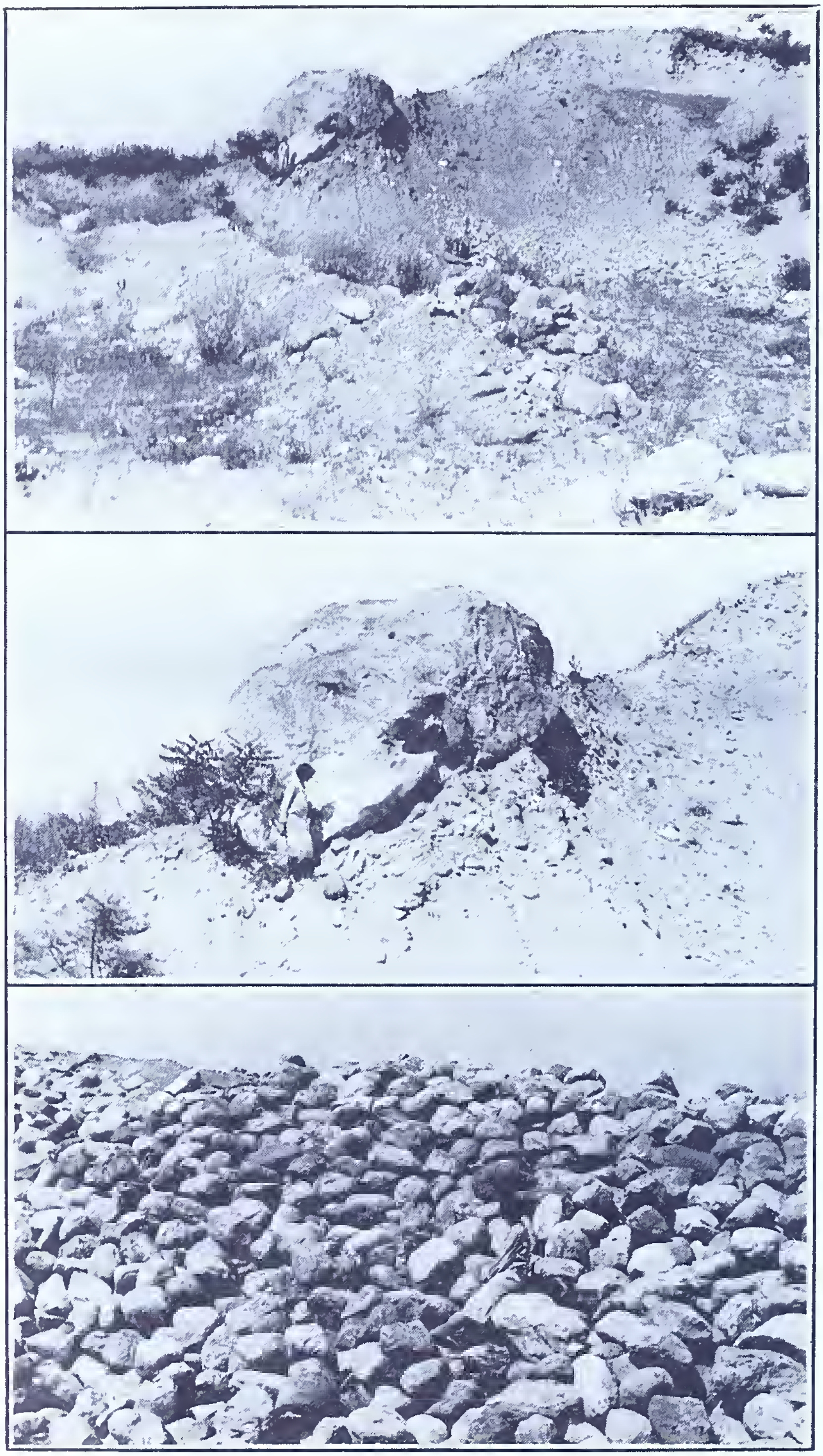
PLATE 5

A. Wisconsin stratified drift at Riegelsville.

B. Wisconsin stratified drift on high terrace near Water Gap 75 feet above river.

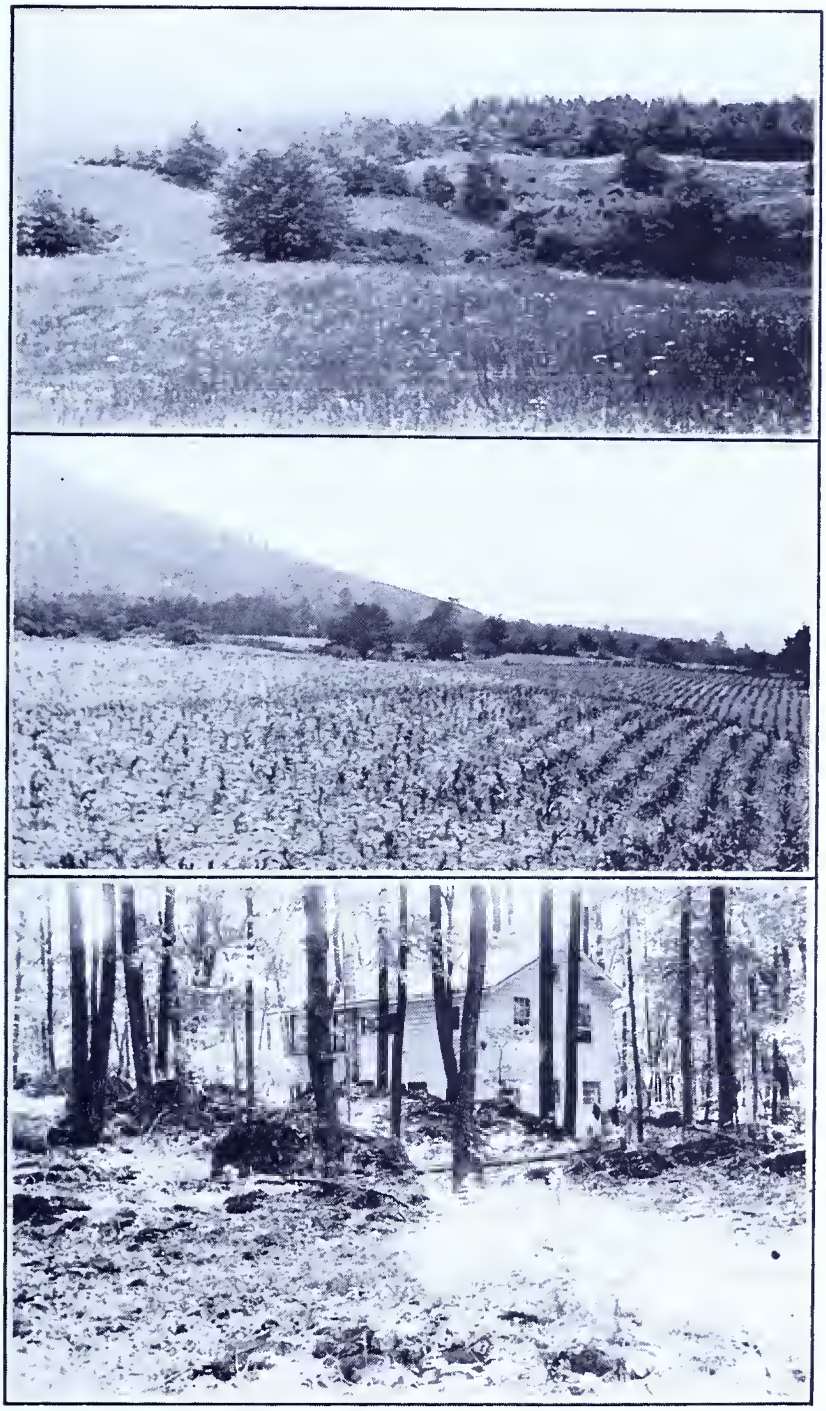
C. Wisconsin stratified drift on Slateford Creek.

PLATE 6



A. Boulders in stratified drift, Jacoby kames.
B. Near view of big boulder as above.
C. Piled oversize boulders, Jacoby kames.

PLATE 7

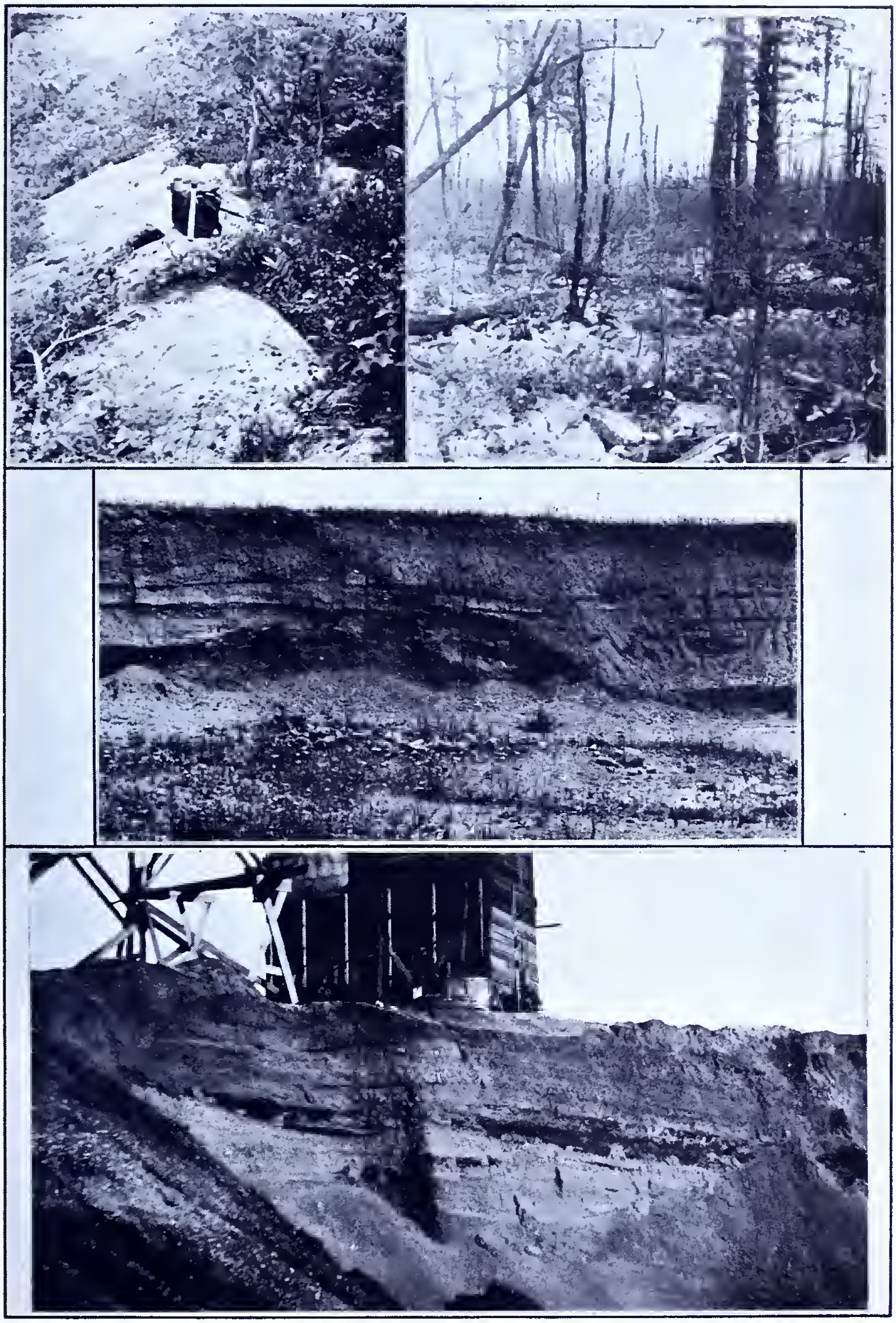


A. Wisconsin terminal moraine west of Bangor.
B. Wisconsin terminal moraine northwest of Bangor.
C. Limestone ledge, small strike ridges.

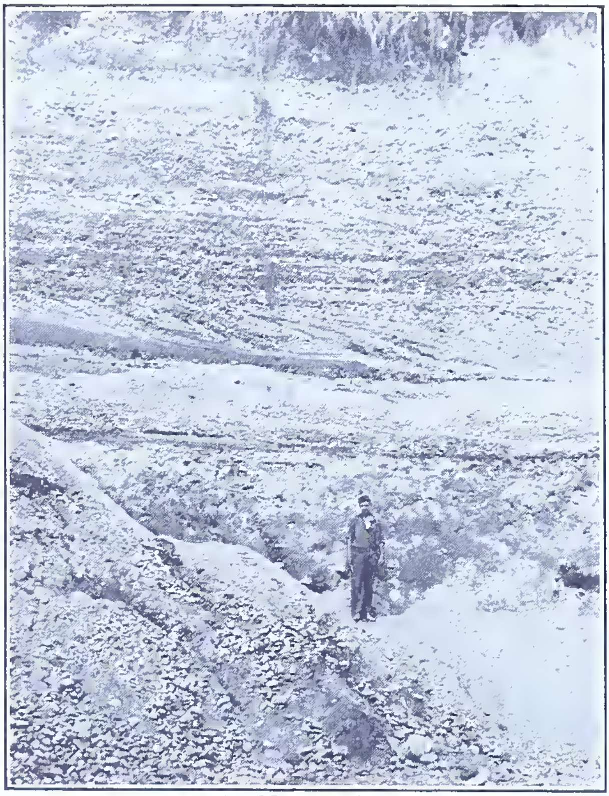
A. Illinoian till northeast of Phillipsburg.

B. Illinoian till in Lehigh Cement Co. quarry southwest of Martins Creek.

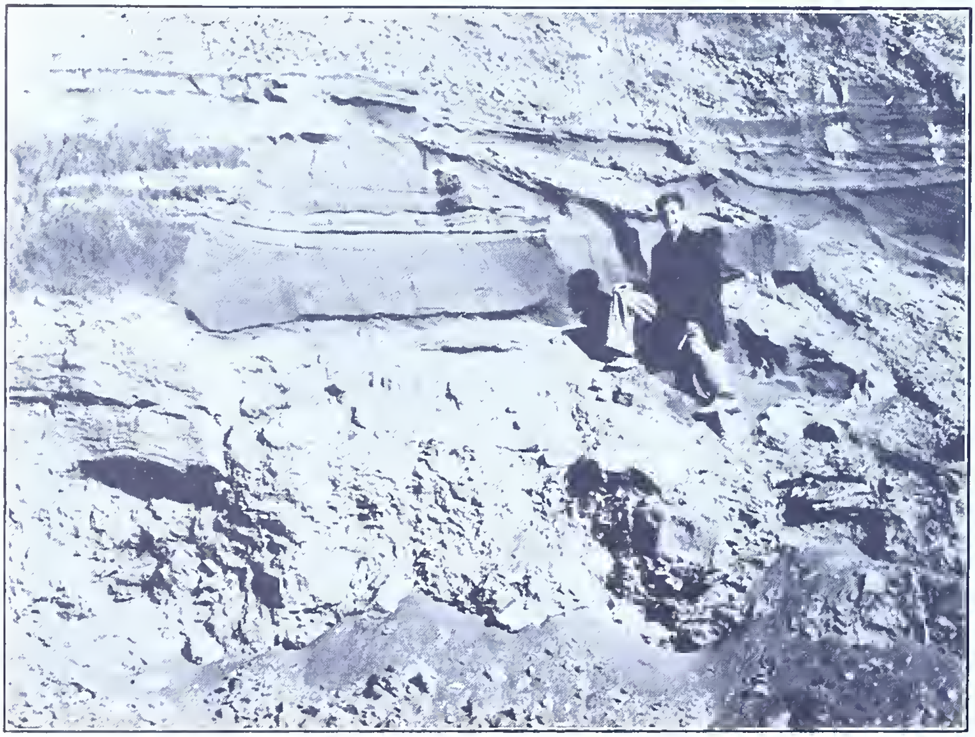
PLATE 9



A. Roche moutoneé on mountain crest (upper left).
B. Residual blocks on mountain crest (upper right).
C. Illinoian stratified drift near Martins Creek.
D. Illinoian stratified drift near Kennedys Station.



A. North side.



Photograph by Mallis.

B. East side, showing weathered limestone boulder opposite man.

Stratified Wisconsin drift on Wisconsin till in gravel pit at Carpentersville.

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